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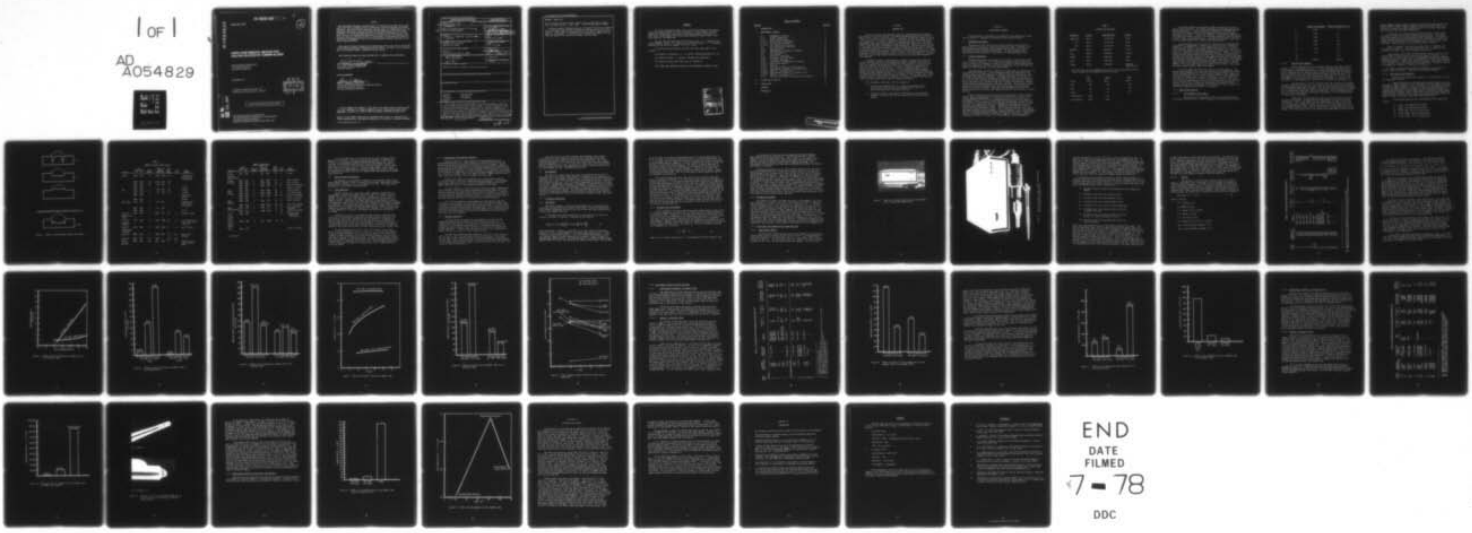

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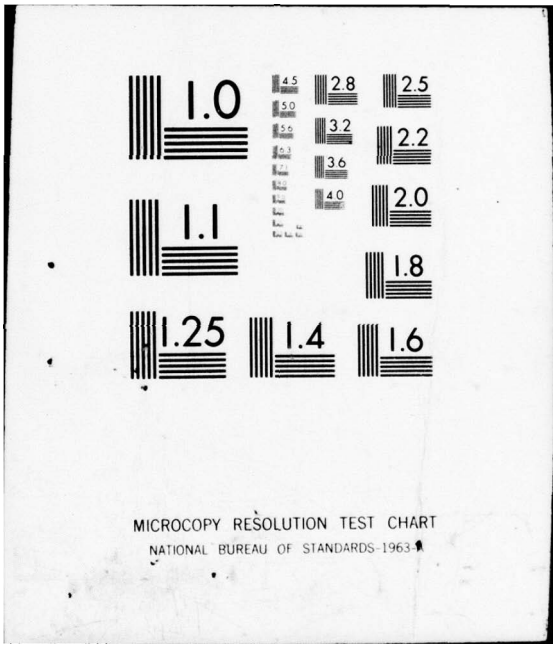
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RAPID CORE REMOVAL METHOD FOR HOLLOW DS EUTECTIC TURBINE BLADES

TRW MATERIALS TECHNOLOGY
23555 EUCLID AVENUE
CLEVELAND, OHIO 44117

DECEMBER 1977

TECHNICAL REPORT AFML-TR-77-207
Final Report for Period July 1976 – July 1977

AIR FORCE MATERIALS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
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This technical report has been reviewed and is approved for publication.

K. S. MAZDIYASNI, Program Manager
Processing and High Temperature
Materials Branch

FOR THE COMMANDER

HENRY C. GRAHAM, Acting Chief
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This report covers work performed in a program to develop a rapid core removal method for DS eutectic turbine blades. Fifteen candidate core materials were evaluated by sessile drop tests for chemical compatability with a molten alloy of the NiTaC-13 composition minus rhenium. Based on the sessile drop test results and preliminary removability studies three candidate materials were selected for removability screening studies using ultrasonic energy in hot water, KOH and NaOH solutions. These materials were 10 mol %MgO

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ABSTRACT (Block 20)

-90 mol % Al_2O_3 and 25 mol % MgO - 75 mol % Al_2O_3 spinels and 3 + mol % SiO_2 - 96.5 mol % Al_2O_3 - .3 mol % MgO - .1 mol % Fe designated as SR800.

Ultrasonic energy, imparted either by an ultrasonic bath or an ultrasonic drill, was shown to be an effective method of removing core material from castings. Proper choice of core material was also shown to be an important factor in core removal. Preliminary results indicate that SR800 is a suitable core material for use with DS eutectic casting systems.

FOREWORD

This Final Engineering Report covers the work performed on the project "Rapid Core Removal Method for Hollow DS Eutectic Turbine Blades," and was prepared by TRW Materials Technology, 23555 Euclid Avenue, Cleveland, Ohio 44117 under United States Air Force Contract F33615-76-C-5330, Project ILIR, TRW Project No. 512-002817-88.

The work was performed under the direction of Dr. T. S. Piwonka as the Program Manager, and Dr. P. N. Atanmo as the Project Engineer. K. S. Mazdiyasni, AFML/LLM was the Technical Manager for the Air Force.

The following contributed to the technical effort described in this program.

Core Materials Preparation - L. M. Johnson, Sherwood Refractories, Inc.

Core Removal Process - T. Derkacs, TRW Materials Technology

This report has been given TRW report No. ER-7921-F.

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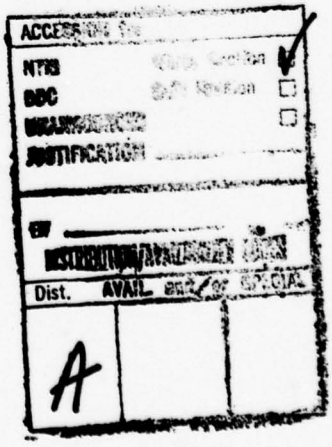

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SECTION I

INTRODUCTION

DS eutectic alloys are candidate alloys for advanced gas turbine engine applications. There are, however, formidable problems associated with the manufacture of DS eutectic turbine hardware. To achieve the desired aligned structure in the alloy as it solidifies, the mold and molten alloy must be exposed to very high temperatures, in excess of 3000°F for extended periods of time. At these temperatures the common investment casting mold and core materials, which contain silica, break down and are attacked by the molten metal. While the condition may be tolerated on the casting exterior, where the affected material may be removed in finishing operations, it is not acceptable in the casting interior, i.e., those surfaces formed by core passages. Thus, the use of silica bearing materials, while undesirable in the mold, must be severely limited in the core material. Alternate materials, such as high alumina spinels and pure alumina, have been proposed as core materials.

A problem is posed by these materials, however, because they cannot be removed from the casting in the conventional manner of subjecting the casting and core to exposure at moderate temperatures and pressures in a caustic autoclave (an operation which dissolves the silica, allowing the remaining core material to fall out of the casting). Instead, a mechanical means of core removal must be used, either by itself, or with thermal/chemical treatments. Because ultrasonic energy has been shown to be an effective method of enhancing conventional core removal processes, it is logical to seek to extend this method to those materials which cannot be removed chemically. At the same time, a more complete survey of candidate core materials is required to define the limits of material systems which can be used for processing eutectics.

TRW, therefore, undertook a two-fold program to:

1) Evaluate the compatability of a variety of candidate ceramic core materials with molten rhenium-free NiTaC-13 alloy to select three potential candidate materials.

2) Evaluate ultrasonic core removal techniques with the candidate materials to select the best core material and the best removal method.

SECTION II

EXPERIMENTAL PROGRAM

The experimental investigation to accomplish this program was divided into two sections: compatability studies and core removal studies.

2.1 Compatability Studies

The purpose of this effort was to select candidate core materials, based primarily on reactivity studies with NiTaC-13 alloy. The effort required selection and manufacture of candidate ceramic bodies and sessile drop tests of NiTaC-13 against these bodies. To reduce program costs, rhenium-free NiTaC-13 was used in the majority of the experimental work.

2.1.1 Ceramic Preparation

Candidate materials were divided into two groups - high alumina, and low or non-alumina ceramics. The high alumina group included various forms of pure alumina, a stoichiometric spinel, and a number of high alumina spinels. These were selected on the basis of previous experience, which indicated that alumina is highly resistant to molten metal attack.

The other group included a number of non-traditional core materials. TiN, $Si_3N_4 \cdot La_2O_3$ and $Si_3N_4 \cdot Y_2O_3$ were proposed as novel core materials for DS eutectics because of high temperature, (1500°C) stability and potential ease of removal from superalloy castings. Cunningham and Wimmer (1) as well as Wills (2) have studied the synthesis and properties of silicon-lanthanide rare earth oxynitrides. Gooding and Parratt (3) have published detailed information on the fabrication of metal oxides and nitrides, including TiN. Because of the promise of these materials, they were included. Also included, at the suggestion of AFML and TRW personnel, were $CaZrO_3$, Y_2O_3, YAG garnet, CeO_2, and yttria-alumina-zirconates. These materials appeared to have thermodynamic properties which might make them attractive for use as cores in eutectic castings.

Ceramic bodies were made from the starting materials listed in Table I. $CaZrO_3$, Y_2O_3, and $Si_3N_4 \cdot Y_2O_3$, were pressed into flat discs for sessile-drop testing against molten NiTaC-13. $Si_3N_4 \cdot Y_2O_3$, sensitive to O_2 and C, was processed differently from the single and mixed oxides used in the balance of the program. A dry pressing mix was prepared from equimolar amounts of Si_3N_4 and Y_2O_3. The powders were mixed in a napthalene-trichoroethane solution, which was then evaporated to dryness. Napthalene functioned as a fugitive binder, subliming completely at 50°C. All mixing was performed with a stainless-steel spatula in a Pyrex beaker. After evaporation of the trichloroethane, the resulting agglomerates were forced through a 50-mesh sieve. Pressing took place in a two-inch (5.08 cm) diameter tool-steel die, followed by reaction sintering at 1750°C for 4 hours in a flowing 48% N_2 - 52% H_2 atmosphere.

TABLE 1

CERAMIC RAW MATERIALS

Material	Purity	Particle Size	Source
Al_2O_3-A17*	99.5+	<10 Microns	Alcoa
-16*	99.5+	<10 Microns	Alcoa
-15*	99.5+	<10 Microns	Alcoa
MgO-M51	99.8	400 Mesh	Fisher
Y_2O_3	99.99	-325 Mesh	Ventron
$CaZrO_3$	99.9	-325 Mesh	Cerac
CeO_2	99.9	-325 Mesh	Cerac
Si_3N_4	98.5+	-325 Mesh	Advanced Materials Eng.

* A15, A16, and A17 are bidispersed high purity slip casting grade alumina. Typical properties and compositions are as follows:

	A15	A16	A17
Al_2O_3	99.5+	99.5+	99.5+
Na_2	.08	.08	.08
SiO_2	.03	.03	.02
Fe_2O_3	.01	.01	.01
Green Density	2.50	2.10	
Fired Density	3.88	3.90	

The ceramic samples were examined at 80X to determine the level of porosity they contained. The samples processed as noted above had approximately 40% porosity. Isostatic pressing at 25,000 psi (172 MN/M^2) of 1.7 inch (4.32 cm) diameter disc prior to reaction sintering gave a modest improvement in porosity. Significant reduction in porosity was achieved by using the above mixing, pressing, and sintering procedures, with the addition of 5 mol % Y_2O_3 to the equimolar mix. The lower melting phase $Si_3N_4 \cdot 3Y_2O_3$ formed at grain boundaries at 1750°C aiding densification.

Y_2O_3 and $CaZrO_3$ were mixed with 4 wt. % additions of Carbowax 6000, dissolved in trichloroethane. Powder and binder were dried, pressed to 15,000 psi (103 MN/N^2) in a two-inch diameter tool steel die in a Carver press, ejected, stacked in MgO saggers with the bottom disc in each series serving to isolate the others from contamination by the sagger. Firing took place in a nichrome wire wound cam controlled furnace. The furnace cycle controlled both specimen heating cooling rate. A twenty to twenty-four hour furnace cycle was used, starting at room temperature and ending at 200-400°C, and holding at the peak temperature of 1190°C for three hours. After removal from the wire wound furnace the sagger and samples were placed in an 800°C Globar furnace. The temperature of this furnace was raised at a rate of 200°C/hr. for three hours, and held at 1450°C for four hours. The samples were then furnace cooled to 800°C and removed.

All discs except the bottom one were cut into 90° segments. The segments were placed on the uncut disc, then disc and segments were placed on the graphite pedestal of a Fairchild Semiconductor crystal grower, and heated to 1700°C for 2 hours in flowing argon, cooled to room temperature, and removed. Samples were invariably discolored; as a result they were given a 4 hour air anneal at 1450°C in the Globar furnace. After sessile-drop tests indicated reaction of both of these materials upon contact with molten NiTaC-13, other mixed oxide compositions were tested including $Y_3Al_5O_{12}$, $2Y_2O_3 \cdot Al_2O_3$, and $MgAl_3O_4$. All compositions used in sessile drop testing were made by the procedure outlined above.

2.1.2 Sessile Drop Testing

2.1.2.1 Alloy Material Procurement

Raw materials were procured to make up a two-pound NiTaC-13 alloy heat without rhenium. Chemical analysis of the melt was as follows:

	Composition Obtained	NiTaC-13 Composition (4)
C	0.45	.5
Ta	8.98	8.1
W	2.83	3.1
Al	4.94	5.4
V	5.54	5.6
Co	3.01	3.3
Cr	3.77	4.4
Re	-	6.2
Ni	Balance	Balance

2.1.2.2 Sessile Drop Procedure

Sessile drop testing of the candidate materials was begun at 3100°F (1704°C) and a .5 atmosphere in argon. At first, specimens were placed on a graphite hearth which was placed within an induction heated graphite susceptor. It was suspected that the specimen might be picking up carbon from the graphite hearth so tantalum foil was placed between the hearth and the specimens. The foil became very brittle and had to be replaced after each run. In the final arrangement the tantalum foil was replaced by a molybdenum foil resting on an Al_2O_3 hearth. The molybdenum foil exhibited no brittleness in subsequent runs.

The temperature of the hot zone was monitored using both an infrared pyrometer focused on the specimen with emissivity set at 1.0 and a W-3% Re/W-25% Re thermocouple located near the sample. The hot zone temperature was controlled by a Pt-Pt+13% Rh thermocouple placed at the edge of the furnace where the temperature is considerably lower than that of the hot zone. This arrangement permits the use of the less expensive Pt-Pt+13% Rh thermocouple for an increased number of cycles before replacement.

Before each run each specimen consisting of the ceramic piece and the metal was weighed. The specimens were then placed in the furnace as described above. The furnace chamber was then pumped down to under five microns, refilled with argon, pumped down again to under five microns before refilling to .5 atmospheres with argon. The furnace hot zone was then heated up to the required test temperature and held for twenty hours. The specimens were furnace cooled. When cool the specimens were removed and weighed again to determine any

weight changes resulting from the process. Although test temperatures were 3100°F (1704°C), 3200°F (1760°C), 3300°F (1816°C), and 3400°F (1871°C), a specimen was tested at a higher temperature only if the lower temperature reactivity test was considered satisfactory.

In addition to the weight change, the metal-ceramic contact angle, the depth of attack and the type of attack were determined. The contact angle was measured on a Jones and Lamson optical comparator. The depth of attack and type of attack were determined from a profilometer trace of the ceramic-metal interface and from a macrograph of the cross section of the interface. Types of attack are classified as shown in Figure 1.

Type W is generally important where edge effect is important such as in melting crucibles. In a casting where the core is completely surrounded by the metal, this type of attack does not occur.

U-type attack occurs where the metal-ceramic reaction results in the "eating away" of part of the core at the metal-ceramic interface. Such attacks result in the reduction of the core passage dimensions by producing protuberances (positive metal) and in the generation of undesirable potential inclusion products. n-type is the opposite of U-type. The reaction results in an increase in the core dimension and consequently an increase in cooling air passage and a reduction in casting wall thickness.

In current conventional DS castings protuberances of the order of 0.0004 - 0.001 inch (0.001 - .0025 cm) are considered acceptable.

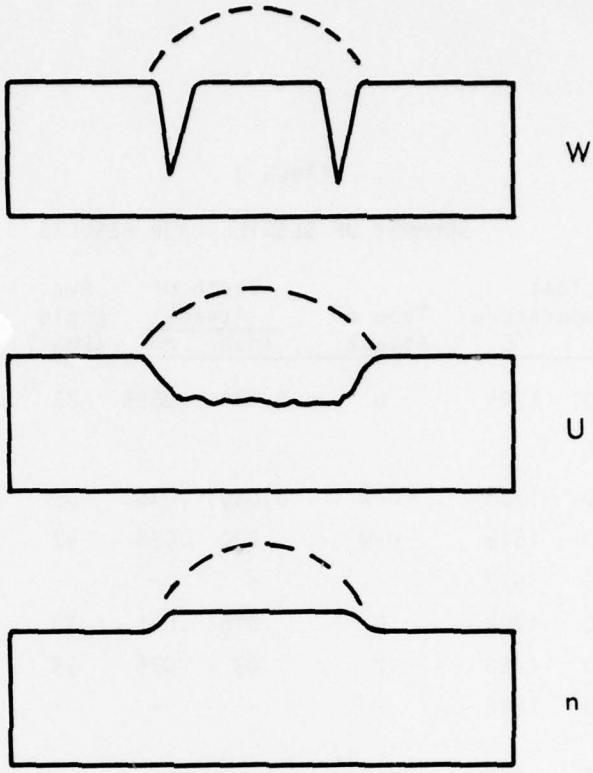
2.1.2.3 Test Results and Discussion

Detailed test results were reported in a previous report (5) and are summarized in Table 2.

None of the materials evaluated performed satisfactorily at temperatures of 3300°F (1871°C) or over. Selection of three candidate materials for removal screening tests was therefore based on the performance at 3100°F (1704°C) and 3200°F (1760°C). Criteria for selection were resistance to cracking and resistance to molten metal attack as measured by contact angle, depth and type of attack, width of the reaction layer and metal penetration. A good material should not crack, should have high contact angle (90°), no depth of attack, no reaction layer and no metal penetration.

The following materials were considered the best among those tested:

1) Al_2O_3 - A17 pressed and sintered.
2) Al_2O_3 - A16 pressed and sintered.
3) 5 mol % MgO - 95 mol % Al_2O_3 spinel.
4) 10 mol % MgO - 90 mol % Al_2O_3 spinel.
5) 25 mol % MgO - 75 mol % Al_2O_3 spinel.



COMBINATIONS OF VARIOUS TYPES CAN OCCUR, I.E.

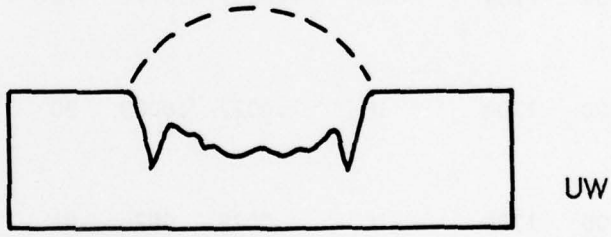


Figure 1. Types of attack between metals and ceramic.

TABLE 2

SUMMARY OF SESSILE DROP RESULTS

Material	Test Temperature °F	°C	Type of Attack	Depth of Attack Inch	cm	Avg. Angle (Deg.)	% Wt. Loss	Other Remarks
$CaZrO_3$	3100	1704	U	0.024	.0635	72		cracked, metal penetration into ceramic
	3200	1760	U-W	0.030	.076	59		"
	3300	1816	U-W	.030	.076	42		"
	3500	1927	-	-	-	-		melted
Y_2O_3	3100	1704	U	.016	.041	36		cracked
	3200	1760	U	.03	.076	39		cracked
	3300	1816	-	-	-	-		metal disintegrated
	3500	1927	-	-	-	-		melted
$Y_2O_3 \cdot Si_3N_4$	3100	1704	U	.016	.041	-		complete metal penetration into ceramic
	3200	1760	U	.03	.076	-		"
	3500	1927	-	-	-	-		melted
Al_2O_3-A17 (reacted with SiN_4)	3100	1704	n	+.0067	.017	78	1.3	powdery surface
Al_2O_3-A17 (injection molded)	3100	1704	W	.0027	.0069	90	4.7	pin holes, reaction layer .003" thick (.0076 cm)
Al_2O_3-A17 (pressed and sintered)	3100	1704	W	.0029	.0074	91	1.1	good interface
Al_2O_3-A15	3300	1816	U	.0166	.042	102	13.7	metal disintegrated
Al_2O_3-A16	3300	1816	U-W	.0052		106	12.3	"
$Y_3Al_5O_{12}$ (Garnet)	3100	1704	U-W	.023	.058	61	1.3	reaction layer .002" (.005 cm) thick

TABLE 2 (Continued)

Material	Test Temperature °F	Test Temperature °C	Type of Attack	Depth of Attack Inch	Depth of Attack cm	Avg. Angle (Deg.)	% Wt. Loss	Other Remarks
$MgAl_2O_4$ (stoichiometric spinel)	3100	1704	U	.076	.066	79	5	cracked
10 MgO-90 Al_2O_3	3100	1704	W	.0013	.0033	112	1	clean interface
	3200	1760	W	.0027	.0069	93	4	small reaction
	3300	1816	W	.0056	.0142	77	23	metal disintegrated
	3400	1871	-	-	-	-	-	melted in furnace
25MgO-75Al_2O_3	3100	1704	W	.0019	.0048	98	1	clean interface
	3200	1760	W	.0074	.0188	88	6	pin holes,cracked
	3300	1816	W	.004	.0102	90	22	metal disintegrated
	3400	1871	-	-	-	-	-	melted in furnace
5MgO-95Al_2O_3	3200	1760	U	.0051	.013	76	17	clean interface,
	3300	1816	n	.0246	.0625	69	43	metal disintegrated
5MgO-95Al_2O_3+.5SiO_2	3200	1760	W	.0046	.0117	71	25	metal penetrated ceramic
	3300	1816	n	.0296	.0752	71	39	metal disintegrated
4Y_2O_3-4Al_2O_3-92ZrO_2	3200	1760	-	-	-	-	+2*	complete metal penetration into ceramic
8Y_2O_3 - 8Al_2O_3-84ZrO_2	3200	1760	U	.043	.1092	76	+8*	"
CeO_2	3400	1871						melted in furnace

* weight gain

It will be noted that all five materials are high in Al_2O_3 content. Removal of core bodies in the Al_2O_3-SiO_2 system becomes increasingly more difficult as the Al_2O_3 percentage increases because Al_2O_3 is not readily dissolved in conventional chemicals which do not also attack the casting. Selection of the three initial materials from this group of five was, therefore, based on the Al_2O_3 content. The 5 mol % MgO spinel, 10 mol % MgO spinel and 25 mol % MgO spinel were selected because they contain less Al_2O_3 and therefore had better potential for removal than the pressed and sintered Al_2O_3 materials.

2.2 Core and Casting Production

The approach to the problem of removal of core materials used a high power density ultrasonic field in conjunction with other techniques, including boiling alkali, abrasive fluid, and ultrasonic drilling. This required the manufacture of core materials and castings.

2.2.1 Core Production

Spinels containing 10 and 25 mol % MgO (instead of the 50 mol % in stoichiometric spinel) were chosen and 1/4" x 1/4" x 2", (6.4mm x 6.4mm x 50.8mm) .43" x .43" x 2" (10.9mm x 10.9mm x 50.8mm) and 1-1/2" x 1/8" x 2" (38.1mm x 3.18mm x 50.8mm) slab specimens were made for casting and core removal studies. Techniques were again identical to those used for sessile drop specimens except that a 3 inch (76.2mm) diameter die was used for pressing at 14,000 psi. Cutting was again done prior to high firing in argon at 1700°C. Some grinding on SiC papers followed by denatured ethyl alcohol rinsing, was necessary to achieve control of thickness and flatness. All dimensions prior to high temperature firing were 10% greater than specified, to allow for shrinkage.

Cracking during the firing operation was a problem. Approximately one-third of the specimens cracked when processed as described above, with slab specimens being more crack-prone than rod specimens. Increasing the heating time from two to four hours in the high firing cycle reduced but did not completely eliminate the cracking problem. As a further precaution the edges and corners of the slabs were polished with 400 grit SiC paper to remove surface cracks which might initiate fracture during the furnace cycle.

For the manufacture of 1-1/2" x 1/8" x 5" slabs of 10 mol % MgO - 90 mol % Al_2O_3 a rectangular die with a cavity 6" x 1.75" was used because of previous experiences with loss of corners on removal from similar dies. Attempts to press specimens with 4 weight percent Carbowax, used previously, resulted in specimen crumbling each time. Increase of the Carbowax content to 6 weight percent, plus gentler handling of as-pressed slabs during removal, enabled removal of specimens intact every time. This allowed production of a sufficient number of slabs of a size to yield 1-1/2" x 1/8" after final firing at 1450°C.

2.2.2 Supplemental Core Material Research

Previous internally funded research and development efforts at Sherwood Refractories, Inc., had produced an injection molded alumina composition containing approximately three percent silica by weight. Control of the type of alumina and particle size distribution provided a composition, Sherwood designation SR-800, which has excellent dimensional control from the green state up to temperature in excess of 1650°C. This material was included in the program for comparison with the alumina-based samples which did not contain silica as to removal rates from sample castings. SR800 contains 3+ mol % SiO_2 - 96.5 + mol % Al_2O_3 - 0.3 mol % MgO - 0.1 mol % FeO.

Although the intent of the program was to concentrate on material systems which were silica-free, SR-800 was selected because it was reasoned that a small amount of silica in the grain boundary phase would provide a higher reactivity path for the chemical degradation of the core.

The small amount of silica which may actually be present, depending on thermal history, as mullite, was not expected to markedly affect the interaction of the core and molten NiTaC type alloys during casting. In addition, the application of ultrasonic energy to the core in a caustic solution was the grain boundary phase and allow the removal of the alumina grains freed by the dissolution of the high silica content grain boundary material.

This 3% silica material system appeared to provide both excellent resistance to metal penetration and reaction and high chemical removal rate. In addition, the economics of producing a precision ceramic core with appropriate quality control standards were very favorable. This is especially true since new technologies and radically different production facilities are not required. For these reasons, the material was added and carried through to the conclusion of the program.

2.2.3 Casting Processing

The required microstructure for a DS eutectic (4) requires that processing temperatures of 3100°F (1704°C) and growth rates of 1/4 in. (.635 cm)/hour are required to obtain planar front solidification. Such processing is time-consuming and expensive. To reduce program costs, no attempt was made to obtain planar front solidification in the manufacture of cast specimens. Instead, castings were solidified from a temperature of 2800°F (1537°C) at a rate of 1 inch (2.54cm) per hour.

Two sets of equiaxed castings containing four 1/4" x 1/4" x 2" cores and four .43" x .43" x 2" cores each of the four materials (5 mol % MgO, 10 mol % MgO, 25 mol % MgO, and 3 mol % SiO_2) were produced in clusters of four per mold. Each core was covered with 1/8 inch thick wax before assembly in the cluster which was then dipped in alumina stucco to form the mold. The alloy was rhenium-free NiTaC 13.

Two directionally solidified castings were produced from a single casting with the 10 mol % MgO core and the 3 mol % SiO_2 core which tests indicated were the most promising of the four being evaluated. The 10 mol % MgO core measured 2" x 2" x 1/8" while the 3 mol % SiO_2 core was a stepped piece of dimensions 1/2" x 1/4" x 1" and 1/2" x 1/8" x 2". The castings were solidified from a mold hot zone temperature of 3100°F (1700°C) at the rate of .25 inch (.635cm) per hour. The alloy was NiTaC 13.

2.3 Core Removal

The basic core removal technique under investigation was the use of high power ultrasonic energy either alone or in conjunction with chemical and mechanical aids. Two methods of applying the ultrasonic energy were investigated, cavitation of a liquid in an ultrasonic tank and ultrasonic drilling in which a tuned ultrasonic horn (drill bit) is used to concentrate the energy in the area of interest. Supplemental techniques investigated included the effect of chemicals in the ultrasonic tank, the effect of different refractory particles (grits) to enhance ultrasonic action, and the effect of prestressing the core prior to application of ultrasonic energy. The following sections describe the theory involved in these tests, present the results both on samples of core material and on actual castings and discuss the conclusions that can be drawn from these results.

2.3.1 Ultrasonic Techniques

2.3.1 Cavitation

When high ultrasonic intensities are generated in a liquid, particle velocities and accelerations can reach large values. Acoustic pressures may reach several atmospheres and, as a result of cavitation, local pressures may be many times greater than this.

It has been shown that the behavior of a gas bubble in a liquid subjected to ultrasonic vibrations is governed by the equation:

$$2R\left[P_o \sin\omega t - P_A + \left(P_A + \frac{2S}{r_o}\right)\frac{r_o^3}{r^3}\right] = 4S + 3\rho r\left(\frac{dr}{dt}\right)^2 + 2\rho r^2\frac{d^2r}{dt^2} \qquad (1)$$

where the bubble, of radius r_o, has radius r at time t when an alternating pressure $P_o \sin\omega t$ is superimposed on the steady state pressure P_A in a liquid of density ρ and surface tension S. R is the universal gas constant. While this equation cannot be solved analytically, a number of specific numerical examples have been evaluated. Although the number of relevant parameters make generalization difficult, some definite conclusions can be drawn. The violence

of the collapse of a bubble is determined primarily by the maximum radius to which it grows. Since the maximum bubble radius is inversely proportional to ω, it is concluded that the higher the ultrasonic frequency the higher the acoustic pressure (energy density) needed to initiate cavitation and the less violent the cavitation at any given energy density. The acoustic pressure that must be achieved to cause cavitation is dependent on the density and surface tension of the liquid and on the ultrasonic frequency. In general, the higher the frequency the higher acoustic pressure (and, therefore, energy density) needed to initiate cavitation (8). This is why ultrasonic cleaners generally operate at relatively low frequencies.

The violent mechanical motion that results from cavitation when high energy ultrasound is generated in a liquid can be used in one of two modes to achieve core removal. In the cleaning mode the strong forces that are generated at the interface between the solid and the liquid as a result of cavitation are used to cause progressive erosion of the solid. This method works most rapidly on materials made up of an aggregate of particles not too tightly bound together. For more solid materials, it can be enhanced by use of a liquid that attacks the material chemically. In the machining mode an abrasive material is added to the liquid and the oscillation of the abrasive particles accelerates chipping away of the solid surface. This technique is most effective for removing brittle materials, and its ability to remove metal is very poor, thus making it ideal for use as a core removal method, provided that an abrasive of suitable hardness and particle size can be found. The abrasive must be harder than the core material and the particles must be large enough so that they do not fall into the pores of the core material.

2.3.2 Ultrasonic Drilling Theory

While ultrasonic drilling or machining can be accomplished directly using an ultrasonic generator, the amplitude of vibration of an ultrasonic generator is relatively small. Therefore, it has been found helpful to enhance the ultrasonic action by using a tapered horn to concentrate the energy in a smaller surface area. While the shape of the horn may be selected to fit the geometry requirements of the particular application, the length must be selected to match the ultrasonic frequency so that the horn will resonate and therefore provide the maximum vibrational amplitude. The length, X_o, of a horn designed to operate at a frequency, f_o, is given by

$$X_o = \frac{1}{2f_o} \quad \frac{E}{\rho} \qquad (2)$$

where E is the elastic modulus and ρ is the density of the horn material (9).

In ultrasonic drilling, an abrasive paste may be placed between a metal vibrator and a brittle material. The brittle material is rapidly removed while the vibrator shows little sign of wear. In the case of core removal, it should be possible to select a suitable abrasive material so that the core can be rapidly removed without damaging the blade. The requirements of the abrasive are the same as those described above to enhance the effect of cavitation.

Ultrasonic techniques rely for their effectiveness on their ability to concentrate enough energy in a given area to cause cracking of the material. The advantage of the ultrasonic drill over the tank is that all of the output energy can be concentrated in a small area and applied at a specific location, such as the core in a casting. Therefore, its removal rate is much higher. The advantage of the tank is that, since it uses a liquid to transmit the energy, it can apply the energy to otherwise inaccessible areas, such as the interior of a casting. In either case the removal rate is enhanced by the availability of stress risers, such as cracks, pores, and chemically induced damage in the material, which can help to concentrate the energy. For removal of cores from castings, therefore, the most effective technique should be to drill out as much material through available access holes and then to remove the rest in an ultrasonic tank if possible containing a liquid that attacks some constituent of the core chemically, but does not attack the metal.

2.3.3 Ultrasonic Equipment

Two types of ultrasonic equipment were used in the program. The first was a 600 watt (w) ultrasonic tank with a power density of about 5.5 watts per square centimeter (w/cm^2). The second was an ultrasonic drill. In the preliminary screening tests a 350 w generator was used with a circular bit with an area of 0.08 cm^2, providing a power density of 4375 w/cm^2 (see Figure 2). In the tests on actual castings, a 700 w generator was used with either the same tip providing a power density of 8750 w/cm^2 or with a rectangular bit with an area of 0.2 cm^2 providing a power density of 3500 w/cm^2 (see Figure 3). Although there were no organized experiments to measure tip wear, it was observed by the operator that this damage was sustained while attempting to drill the very hard 10 mol % MgO - 90 mol % Al_2O_3 core material. No observable damage was sustained during drilling of the more easily removable materials, although previous experience indicates that a small amount of wear does occur with extended use.

2.3.4 Preliminary Core Removability Screening Tests

2.3.4.1 Experimental Method

The preliminary screening tests were run on samples of core materials, approximately 1.2cm in diameter and 0.3 to 0.5cm thick. The procedure was to rinse each specimen in distilled water and dry it in an oven at 93°C (200°F) and then to weigh it. The specimen was then run through the ultrasonic removal process and the rinse, dry and weigh process was repeated. The core removal

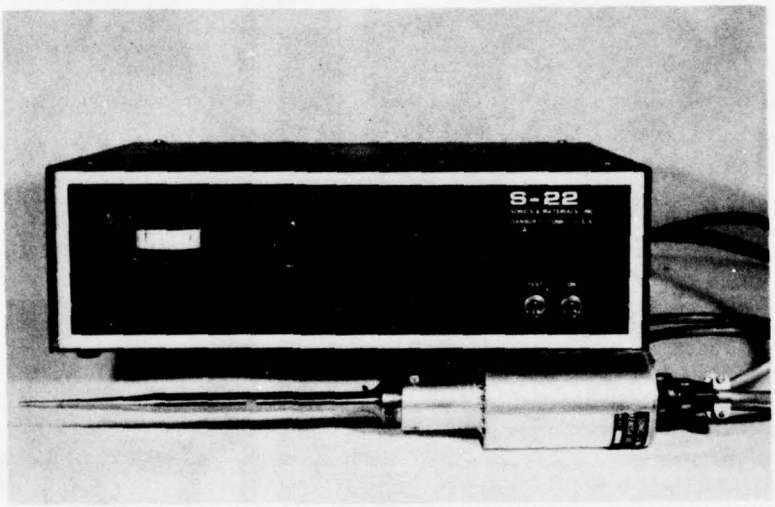


Figure 2. 350 watt ultrasonic power supply and generator with circular cross section bit.

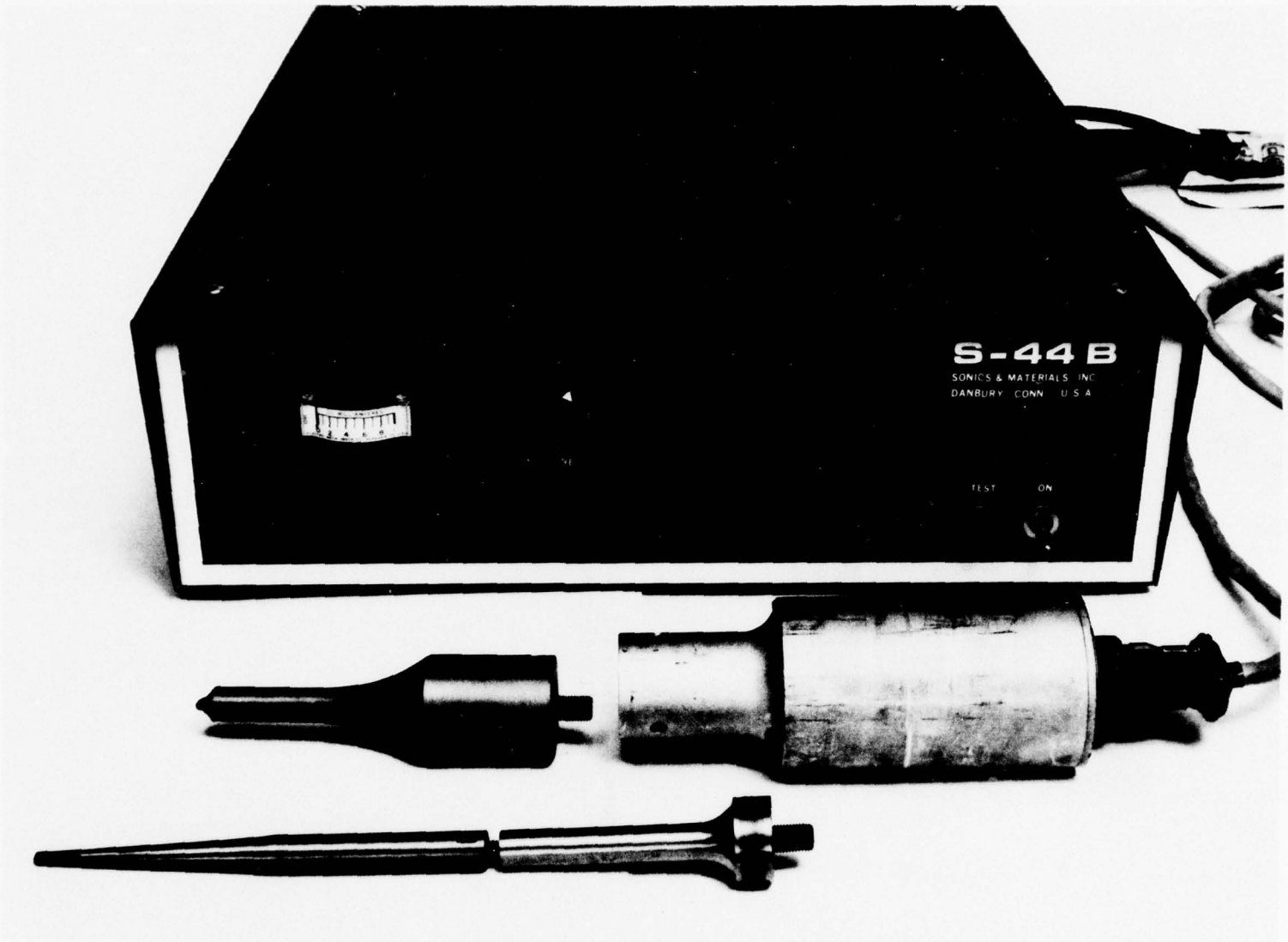


Figure 3. 700 watt ultrasonic power supply and generator with round and rectangular bits.

rate was calculated in units of 10^{-5} cm/hr, a unit of penetration rate, in order to provide a direct comparison with other investigators (Ref. 10). In addition, in order to provide a number with an obvious practical meaning, the time to remove a 5 gram (g) core was also determined. It should be noted that these two measures do not always give relatively corresponding results. In the ultrasonic tank, the penetration rate applies to the entire exposed surface, whereas with the ultrasonic drill, it only applies to the cross-sectional area of the drill. Therefore, comparison of the penetration rates of the two methods may be misleading. For this reason, the time to remove a 5g core gives a much more realistic comparison between methods and materials.

The purpose of the screening tests was to obtain comparison data on a number of core materials and removal processes without the expenditure of time and money required to use actual castings. Initially, samples of 10 mol % MgO - 90 mol % Al_2O_3 and 25 mol % MgO - 75 mol % Al_2O_3 soft fired to 760°C were run under the following eight sets of conditions:

1) Ultrasonic tank with water at unheated equilibrium temperature (65°C).

2) Ultrasonic tank with water heated at 93°C.

3) Ultrasonic tank with saturated KOH at 93°C.

4) Ultrasonic tank with saturated NaOH at 93°C.

5) Ultrasonic drill with water at room temperature.

6) Ultrasonic tank with saturated KOH at 93°C after ultrasonic drilling.

7) Ultrasonic tank with saturated KOH at 93°C and 80 grit SiC, after ultrasonic drilling.

8) Ultrasonic tank with saturated KOH at 93°C and 320 grit diamond.

These tests were selected to verify the effects expected from theory. The test using unheated water (65°C) at equilibrium with the energy input from the ultrasonics was used as a baseline for comparison. Soft-fired discs were used so that the tests could be run in a reasonable time period. The water at 93°C was run to verify the increase of removal rate with temperature. The solutions of NaOH and KOH at 93°C were run to verify the benefit of using chemical attack to enhance the removal rate. The drill tests were run to verify the effect of increased power density. The drilled specimens were subsequently run in the tank also, to determine whether residual damage from the drilling operation would improve the removal rate in the tank. The tests using SiC and diamond grit were run to determine whether or not these materials had

suitable properties to enhance the effect of cavitation. For the test with SiC grit the ultrasonic drill was used to dish out the specimens to hold the grit. Therefore, improvement over the specimens drilled and run in hot KOH without grit was expected as an effect of the grit. Additional tests were run using samples of these same materials plus 5 mol % MgO-95 mol % Al_2O_3 all hard fired to 927°C as they would be before use in casting. One specimen of each material was run using the ultrasonic drill in water and two of each were run in NaOH at 93°C in the tank. These tests were run to verify that the 5% MgO material is the most difficult to remove, and to get some idea of the variability of the process by comparing identical specimens.

2.3.4.2 Results

The results of the preliminary screening tests are listed in Table 3. The removal rate is expressed in units of depth of penetration into the exposed surface per unit time, which is obtained by dividing the weight loss by the material density, the exposed surface area, and the run time. In the case of the disk shaped samples in the tank where they are attacked on all sides, and assuming a constant linear removal rate over the entire surface, the removal rate is obtained by solving the cubic equation:

$$A\alpha^3 + B\alpha^2 + C\alpha - W = 0 \qquad (3)$$

where $A = \frac{3}{2}\pi\rho T$,

$B = \pi\rho T^2(2D_o + T_o)$

$C = \pi\rho(D_o^2/2 + D_o T_o)$

α = removal rate in cm/hour

ρ = density in g/cm^3

T = run time in hours

W = weight loss in time, T, in grams

D_o = initial specimen diameter in cm

T_o = initial specimen thickness in cm

Table 3. Preliminary Core Removal Screening Tests

Sample No.	Material (1) %MgO-%Al_2O_3	Method	Run Time, T hrs	Weight Loss, W mg	Removal Rate, α, 10^{-5} cm/hr	Time to Remove 5g Core, hrs
1	25-75	Water (65°C)	6	0.2	2	150,000
2	10-90	" "	"	"	2	150,000
3	25-75	Water (93°C)	"	1.6	13	18,000
4	10-90	" "	"	0.3	3	100,000
5	25-75	KOH (93°C)	"	13.9	115	3,600
6	10-90	" "	"	7.4	80	4,000
7	25-75	NaOH (93°C)	"	21.2	244	1,400
8	10-90	" "	"	7.9	64	3,800
9	25-75	Ultrasonic Drill	0.1	139.6	342,000	3.6
10	10-90	" "	0.1	209.0	352,000	2.4
9 (2)	25-75	KOH (93°C)	6	29.4	251	1,000
10 (2)	10-90	" "	"	3.8	41	8,000
11	25-75	KOH (93°C)	"	28.4	242	1,100
12	10-90	with SiC Grit	"	8.8	96	3,400
13	25-75	KOH (93°C)	"	12.4	102	2,400
14	10-90	with Diamond Grit	"	6.8	74	4,400
15	5-95	Ultrasonic Drill	0.25	3.9	1,020	7,700
16	10-90	" "	"	12.6	5,490	2,400
17	25-75	" "	"	85.8	46,400	350
18	5-95	NaOH (93°C)	27	1.6	4.0 } ave.	84,000
19	5-95	" "	"	0.3	0.7 } 2.4	450,000
20	10-90	" "	"	3.8	9.0 } ave.	35,000
21	10-90	" "	"	0.9	2.0 } 5.5	115,000
22	25-75	" "	"	3.1	6.4 } ave.	43,000
23	25-75	" "	"	2.3	4.0 } 5.2	59,000

(1) Specimens 1-14 were fired to 760°C. Specimens 15-23 were also fired to 927°C.
(2) Specimens 9-10 were run in KOH (93°C) after ultrasonically drilling a hole through the specimens.

This equation can easily be solved for α using Newton's method of successive approximations (9). This is done by using an initial value, α - C/2B and then calculating a new value, $\alpha_{KH} + \alpha_K - f(\alpha_K)/f'(\alpha_K)$, where $f(\alpha_K)$ is equation (1) evaluated at the specific value (α_K) and $f'(\alpha_K)$ is the first derivative of Equation (1) evaluated at that value. This process is repeated until the change in α becomes insignificant. In tests employing the ultrasonic drill, the area is a constant, the surface area of the drill tip, and a straightforward calculation can be made.

Results of tests run in the ultrasonic bath yielded few surprises. In all cases the 10% MgO-90% Al_2O_3 core was more difficult to remove than the 25% MgO-75% Al_2O_3 material. As expected, raising the bath temperature improved the removal rate (Figure 4). The use of a saturated solution of KOH or NaOH also improved the core removal rate, as shown in Figure 5; it appears that NaOH is the more effective with the 25% MgO material and KOH the more effective with the 10% MgO material. SiC grit additions also appear to be of some benefit (Figure 6), whereas diamond additions do not. However, the relatively small improvements that are obtained (less than an order of magnitude) indicate that the use of an ultrasonic bath to remove cores will be an inefficient method if used by itself.

To obtain a dramatic increase in core removal rate, it was shown that an ultrasonic drill must be used. For soft fired cores (given a single fire at 760°C) an increase in removal rate of nearly 4 orders of magnitude over the best bath techniques is found (Figure 7). This suggests that a possible core removal strategy would be to drill as much of the core as possible out of the casting, and then remove the rest by the ultrasonic bath. As shown in Figure 8, predrilling has only moderate effect on the bath removal rate, neither dramatically accelerating or retarding it. Thus, a composite core removal time would consist of both the drill time and the bath time.

The effect of core processing on core removal time must also be considered. As shown in Figure 7, subjecting the cores to a further firing at 927°C after the first firing at 760°C makes them much more difficult to remove (i.e., the high temperature fired cores have a lower core removal rate than the low temperature fired cores). Even cores which are obstensibly processed identically (Runs 18 and 19, 20 and 21, and 22 and 23) show some variation in removal rates, which is believed to be due to slight differences in their manufacture.

Core removal times have been plotted in Figure 9. Again, it is shown that core removal becomes more difficult as the MgO content decreases. At this point in the program the 5% MgO - 95% Al_2O_3 core was dropped from further testing and the SR-800 core was substituted.

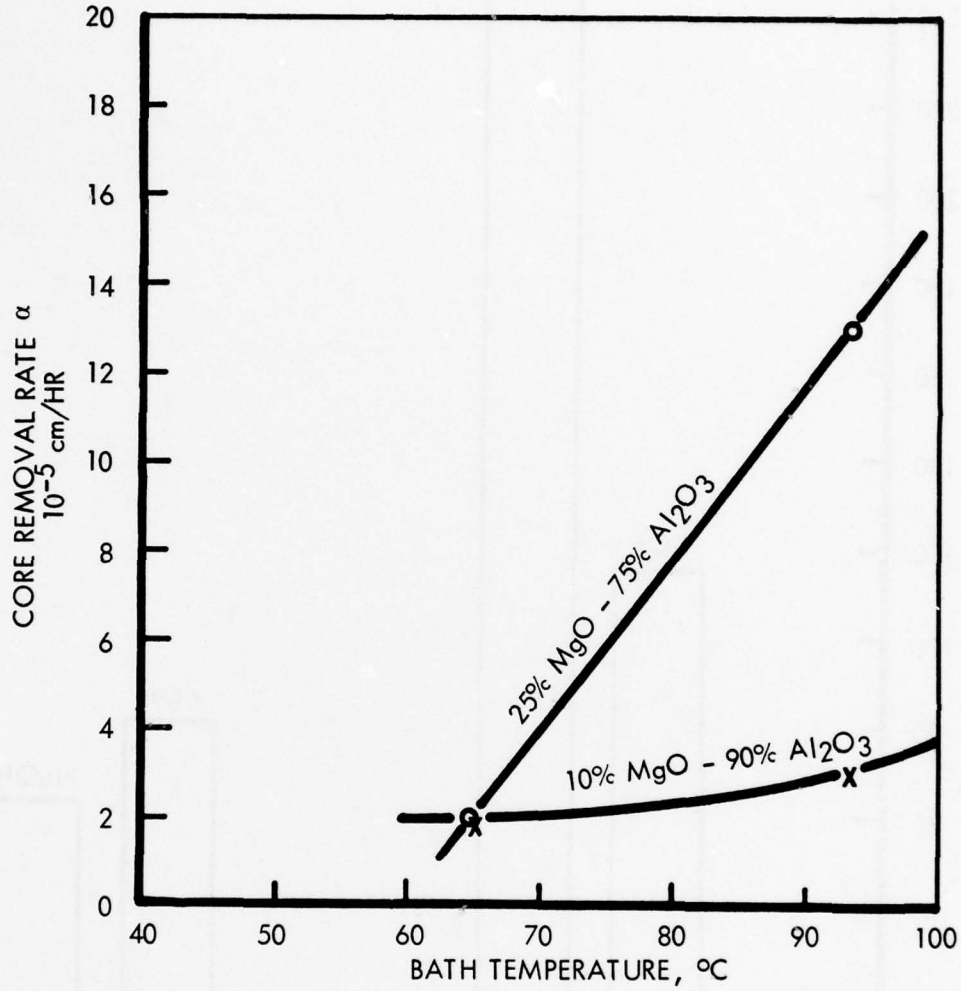


Figure 4. Effect of bath temperature on removal rate in an ultrasonic bath.

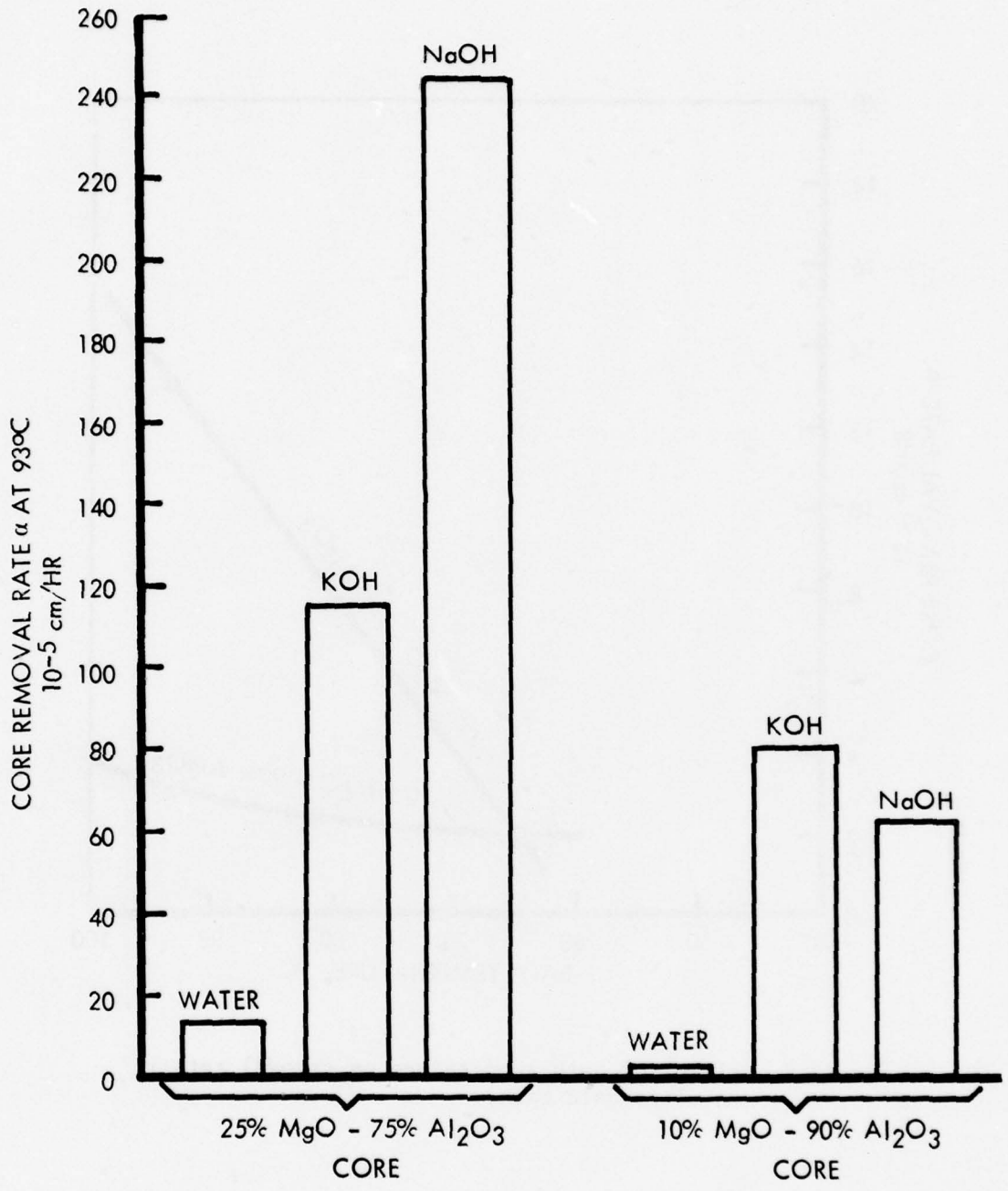


Figure 5. Effect of caustic solutions on removal rate in an ultrasonic bath.

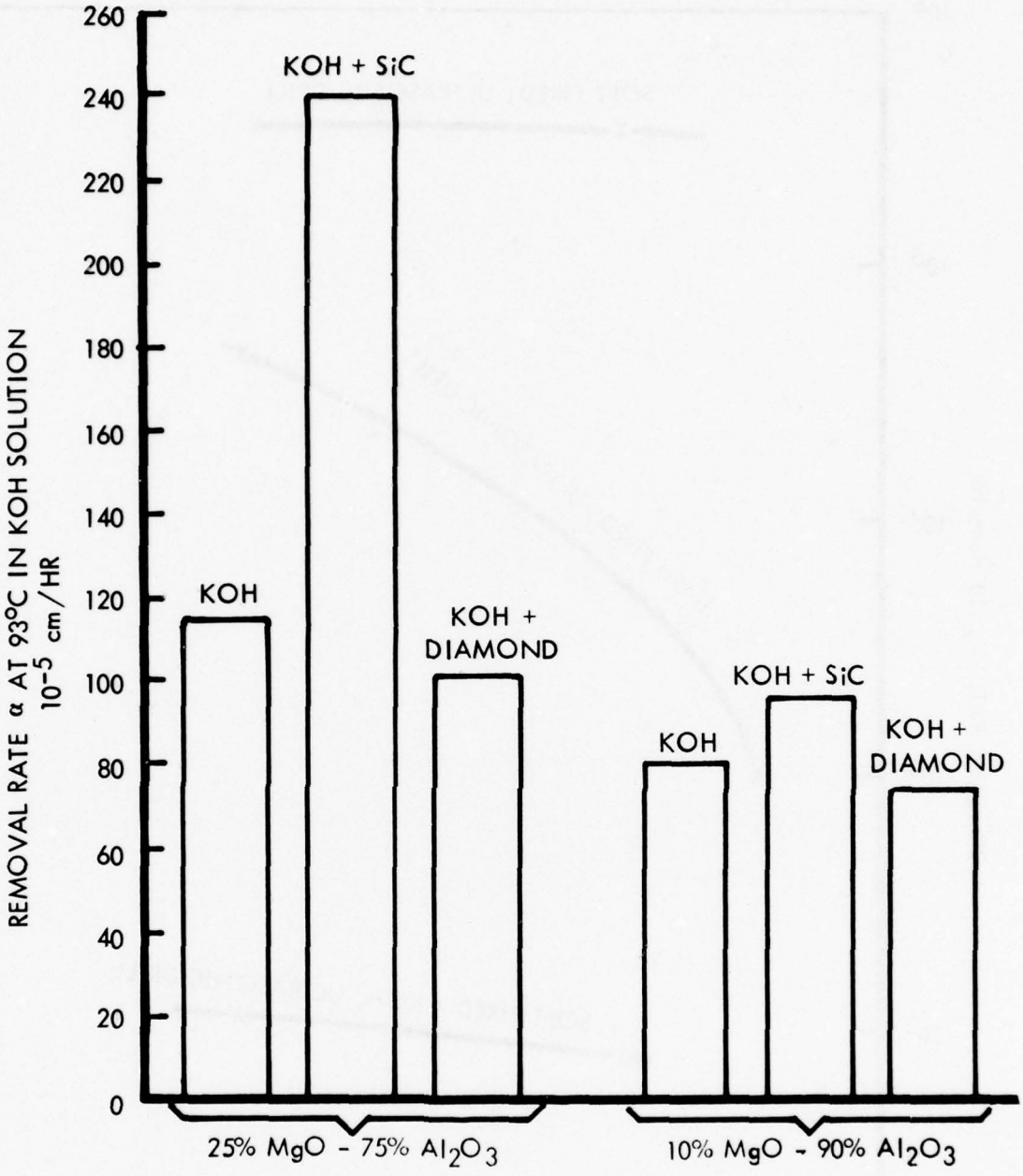


Figure 6. Effect of grit additions on removal rate in an ultrasonic bath.

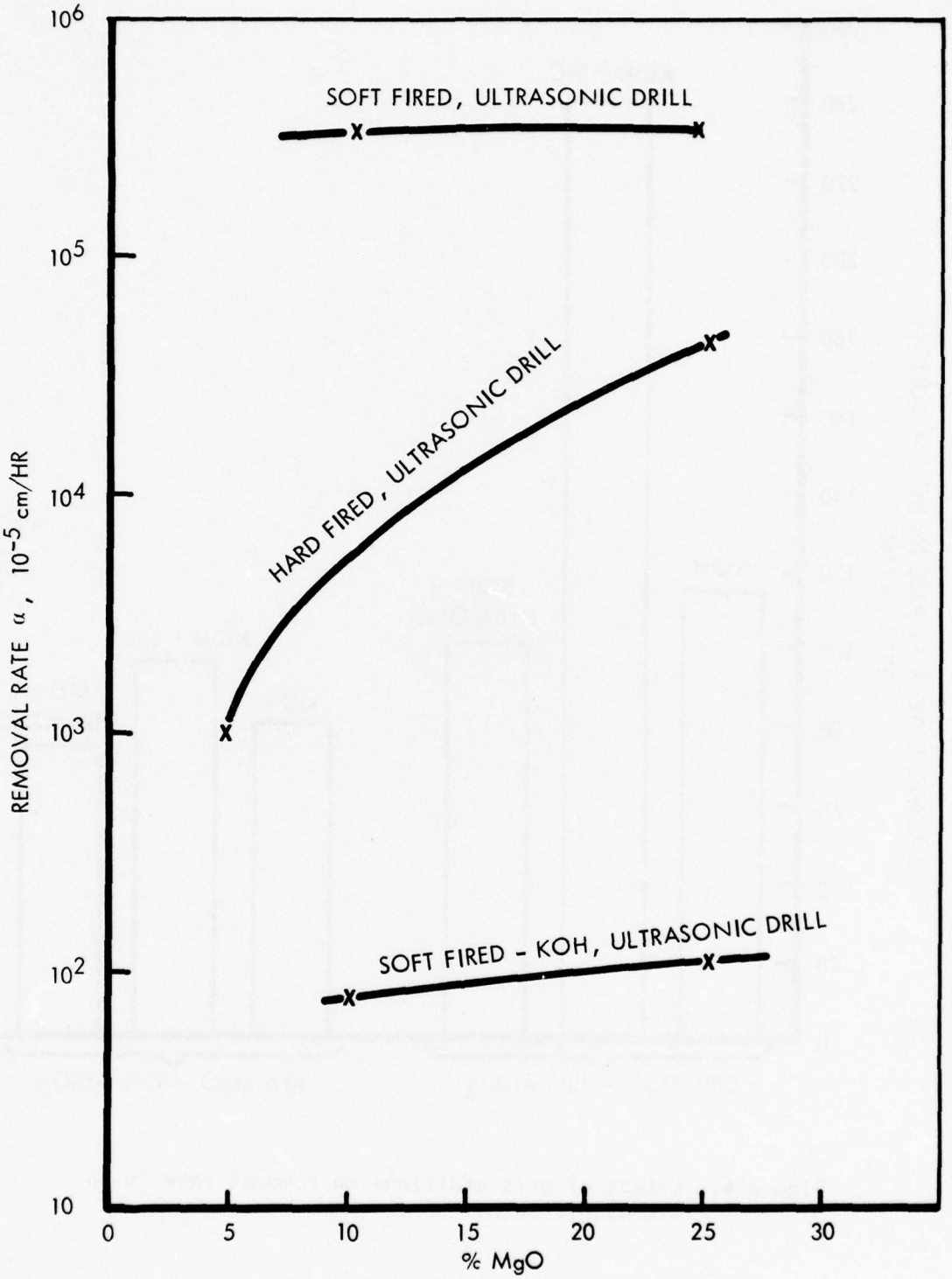


Figure 7. Effect of ultrasonic drilling on removal rate.

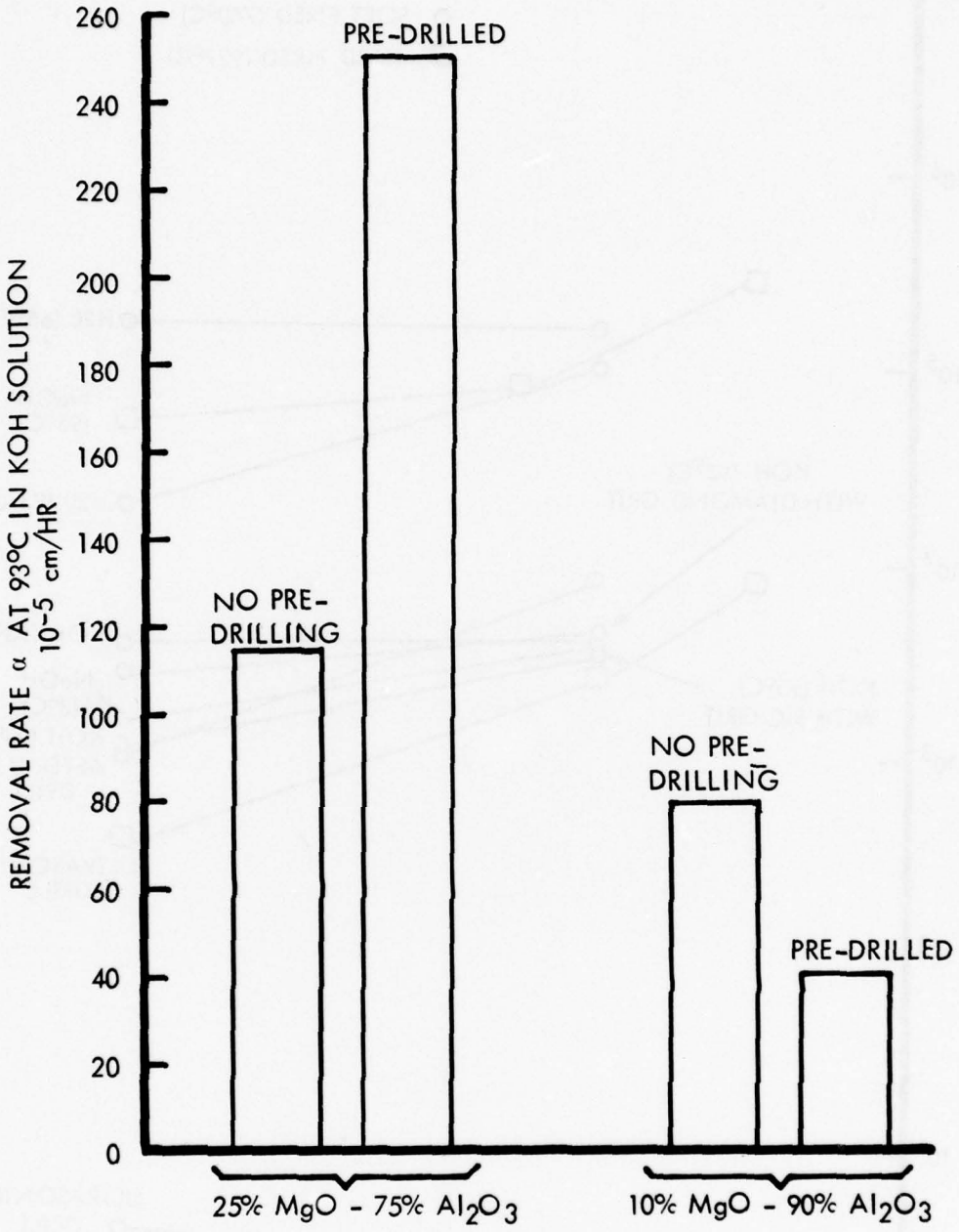


Figure 8. Effect of pre-drilling on removal rate in an ultrasonic bath.

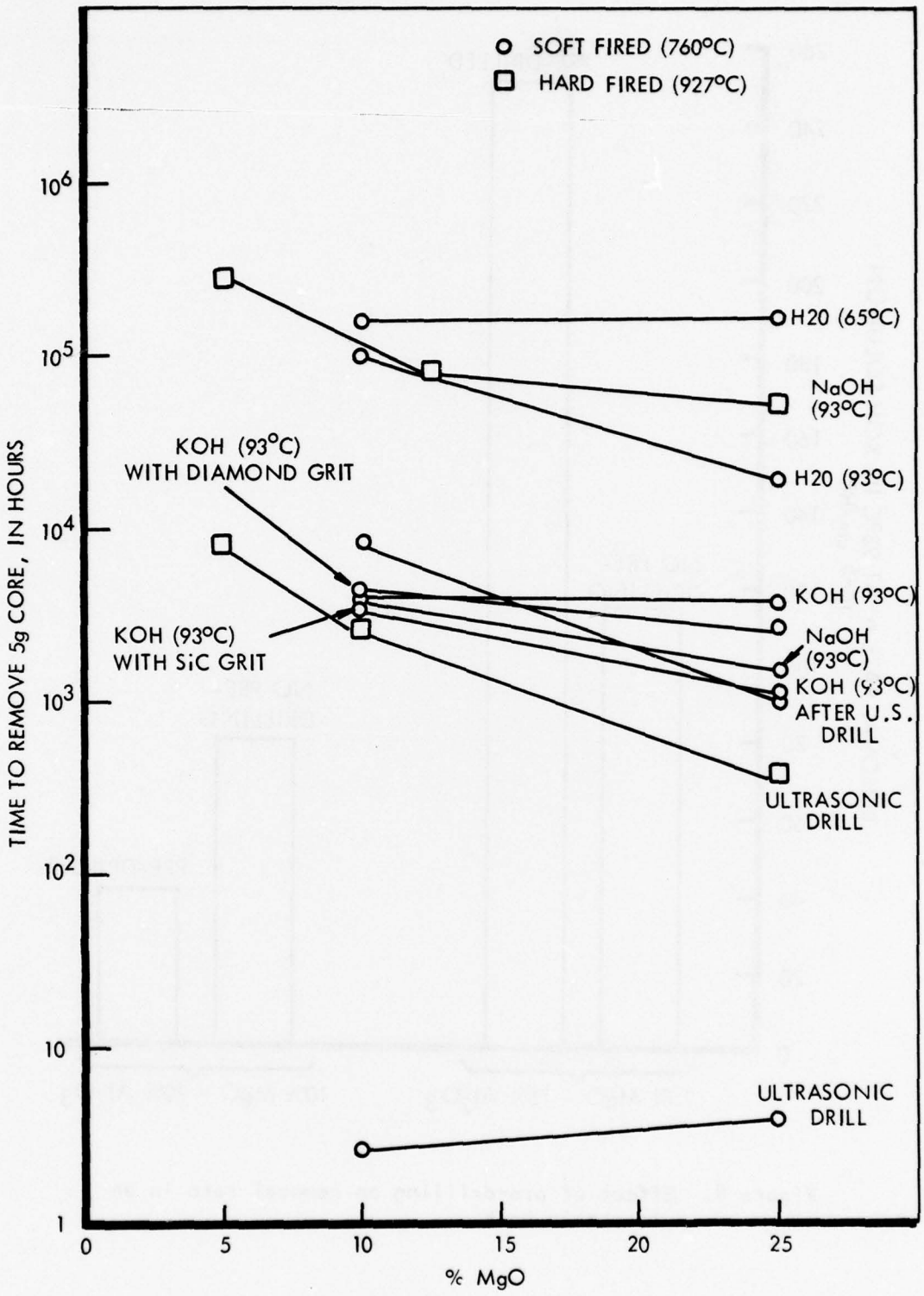


Figure 9. Time to remove 5 grams of material under various conditions.

2.3.5 Core Removal Tests on Actual Castings

2.3.5.1 Experimental Procedure - Ultrasonic Tank

The experiments on actual castings were carried out using the same ultrasonic tank used on samples of core material. For the drilling tests, however, a 700 W generator was obtained to replace the 350 W generator previously used and three different drill bits were tried. A flat bit 8mm square was tried briefly and found unsatisfactory. Extensive testing was done with a rectangular bit 3 x 6mm at the tip and the 3mm diameter round bit which was previously used on the samples of core material.

The majority of testing was done on castings 41mm long with a 6.4mm square core. Some castings with 10% MgO cores were made with 11mm square cores and 3.2 x 32mm cores which have the same surface area but different metal to core perimeters. The cores of SR800 were 12.7mm wide and were stepped so that they were 4.8mm thick on one end and 2.4mm thick on the other.

2.3.5.2 Results - Ultrasonic Tank

The results of the experiments run in the ultrasonic tank are listed in Table 4. One casting each with 10% MgO and 25% core material was run in KOH and NaOH at 93°C for ten hours to determine which chemical is more effective in enhancing the removal rate. For both core materials the KOH was found to be more effective (see Figure 10). The specimen with 10% MgO core material was then run to an accumulated total of 112.5 hours in NaOH. The average removal rate during this time was somewhat lower than during the first ten hours. In spite of the fact that 0.4g of core material was removed during this test, the volume of the core was not significantly reduced. Rather, the entire structure became heavily pitted, indicating the selective removal of a discontinuous certain phase of the material.

These results suggested that if the phase could be made continuous, the core removal rate might be enhanced. This was first attempted by mechanically stressing the casting and core. While there are a number of methods available for doing this to actual blades (a hot die system designed to torque the airfoil slightly, for example), they would be expensive to test. Therefore, a simple test was selected to evaluate the principle. The castings were subjected to alternating stress and ultrasonic cycles. The stress cycle consisted of applying a load of 350 MN/m^2 on each of two sides 90° apart. The ultrasonic cycle consisted of five 6-hour runs in the ultrasonic tank. The general pattern observed in these tests was that during compression the ends of the core cracked and large pieces of material were removed. Then, during the first 6-hour run in the ultrasonic tank, considerably more material was removed, apparently that which was cracked but did not fall out during compression. In subsequent runs in the ultrasonic tank, the removal rate dropped to a value comparable to an uncompressed part. It was concluded from these results that a somewhat higher

Table 4. Core Removal Tests on Castings Using Ultrasonic Tank

Sample No.	Material %MgO-%Al_2O_3	Cross-Sectional Geometry	Method	Run Time, T, hrs	Wt Loss, W, mg	Removal Rate α, 10^{-5}cm/hr	Time to Remove 5g Core, hrs
As Cast							
1	10-90	6.4 mm square	KOH (93°C)	10	142.9	1170	350
2	10-90	"	NaOH (93°C)	10	50.4	450	990
3	25-75	"	KOH (93°C)	10	56.8	600	880
4	25-75	"	NaOH (93°C)	10	29.4	310	1700
2	10-90	"	NaOH (93°C)	112.5 (1)	403.1	320	1400
5	25-75	"	KOH (93°C)+stress	132 (2)	5441.7	> 4300	< 122
6	10-90	"	KOH (93°C)+stress	318	5330.6	1510	300
7	0.3-96.5	Rectangular (3)	KOH (93°C)	78 (2)	6997.4	> 7700	< 56
After Ultrasonic Drilling							
2	10-90	6.4 mm square	KOH (93°C)	30	774	2310	194
4	25-75	"	"	30	32	110	4550
11	0.3-96.5	Rectangular (4)	KOH (93°C)	83 (6)	3573	> 3700	< 116
8	"	Rectangular (5)	"	12 (2)	976	> 5300	< 63
18	"	Rectangular (3)	"	53	6036	9800	44
15	10-90	6.4 mm square	KOH (93°C)	30	57	170	2630
17	25-75	"	"	30	104	370	1450
19	10-90	3.2x32 mm	"	23	1080	1700	106
20	"	"	"	23	2910	4600	40
21	"	"	"	23	160	250	720
22	"	"	"	23	260	410	440

1 Includes 10 hrs previously listed.
2 Last of core removed during last 6 hr. run.
3 Stepped core 12.7 mm wide, 4.8 mm thick on one end and 2.4 mm thick on the other.
4 Same as above with 1.5 cm piece cut off large end.
5 Piece cut off large end as described above.
6 Last of core removed during last 3 hr. run.

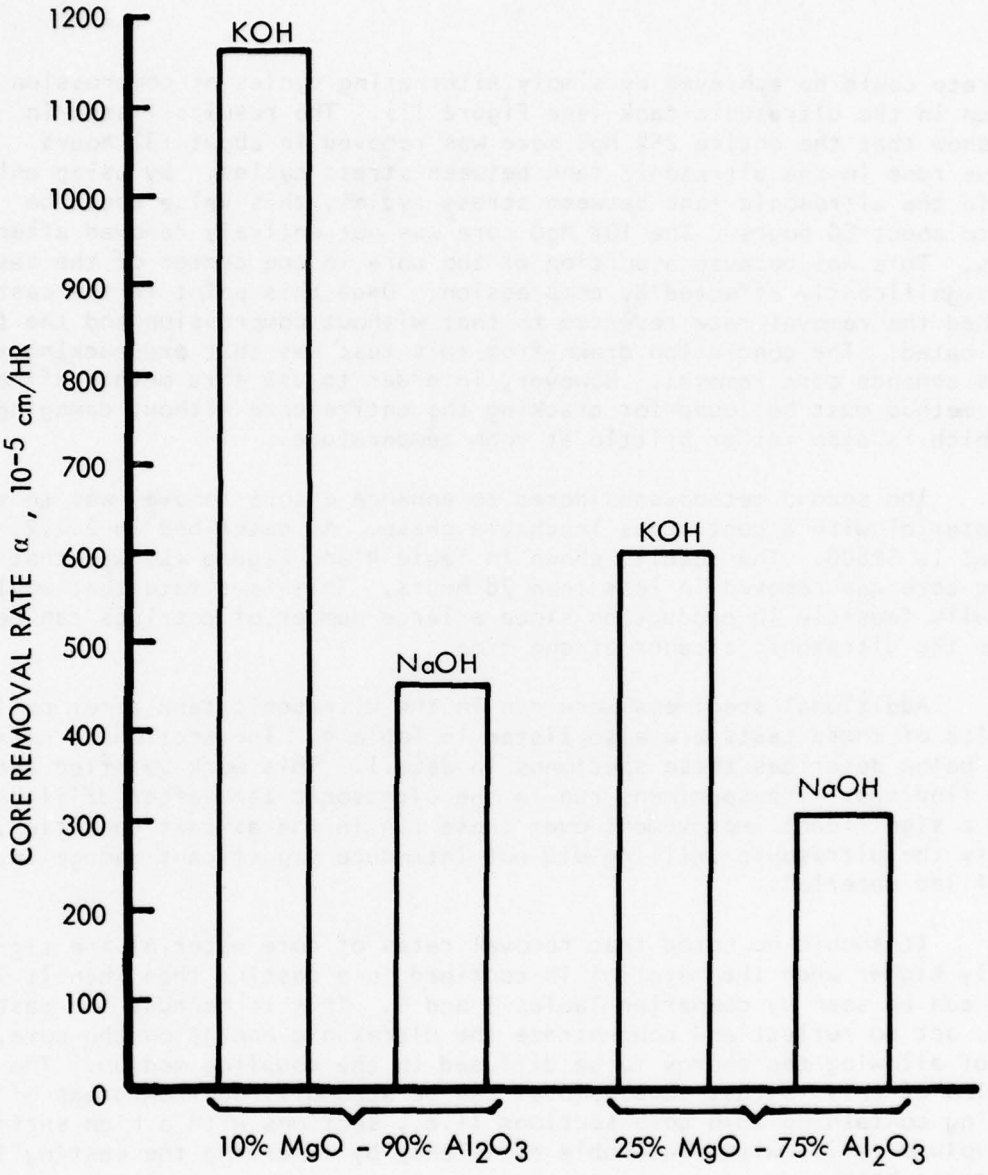


Figure 10. Effect of caustic solution composition on core removal rate in an ultrasonic bath.

removal rate could be achieved by simply alternating cycles of compression with a run in the ultrasonic tank (see Figure 11). The results listed in Table 4 show that the entire 25% MgO core was removed in about 132 hours using five runs in the ultrasonic tank between stress cycles. By using only one run in the ultrasonic tank between stress cycles, this value could be reduced to about 50 hours. The 10% MgO core was not entirely removed after 318 hours. This was because a portion of the core in the center of the casting was not significantly affected by compression. Once this point in the casting was reached the removal rate reverted to that without compression and the test was terminated. The conclusion drawn from this test was that precracking the core does enhance core removal. However, in order to use this method effectively, a method must be found for cracking the entire core without damaging the metal, which is also rather brittle at room temperature.

The second method considered to enhance a core removal was to select a core material with a continuous leachable phase. As described in 2.2.2, such a material is SR800. The result, shown in Table 4 and Figure 12, was that the entire 7g core was removed in less than 78 hours. This is a rate that would be economically feasible in production since a large number of castings can be placed in the ultrasonic cleaner at one time.

Additional specimens were run in the ultrasonic tank after drilling. The results of these tests are also listed in Table 4. The section on ultrasonic drilling below describes these specimens in detail. This work verified the preliminary findings: the specimens run in the ultrasonic tank after drilling did not show a significant improvement over those run in the as-cast condition. Apparently the ultrasonic drilling did not introduce significant damage into the undrilled material.

It should be noted that removal rates of core material are significantly higher when the material is confined in a casting than when it is free, as can be seen by comparing Tables 3 and 4. This is because the casting walls act to reflect and concentrate the ultrasonic energy on the core, instead of allowing the energy to be diffused in the coupling medium. The implication of this is that core removal can be accomplished from areas of the casting containing thin core sections (i.e., sections with a high surface area to volume ratio) with reasonable efficiency by immersing the casting in an ultrasonic bath.

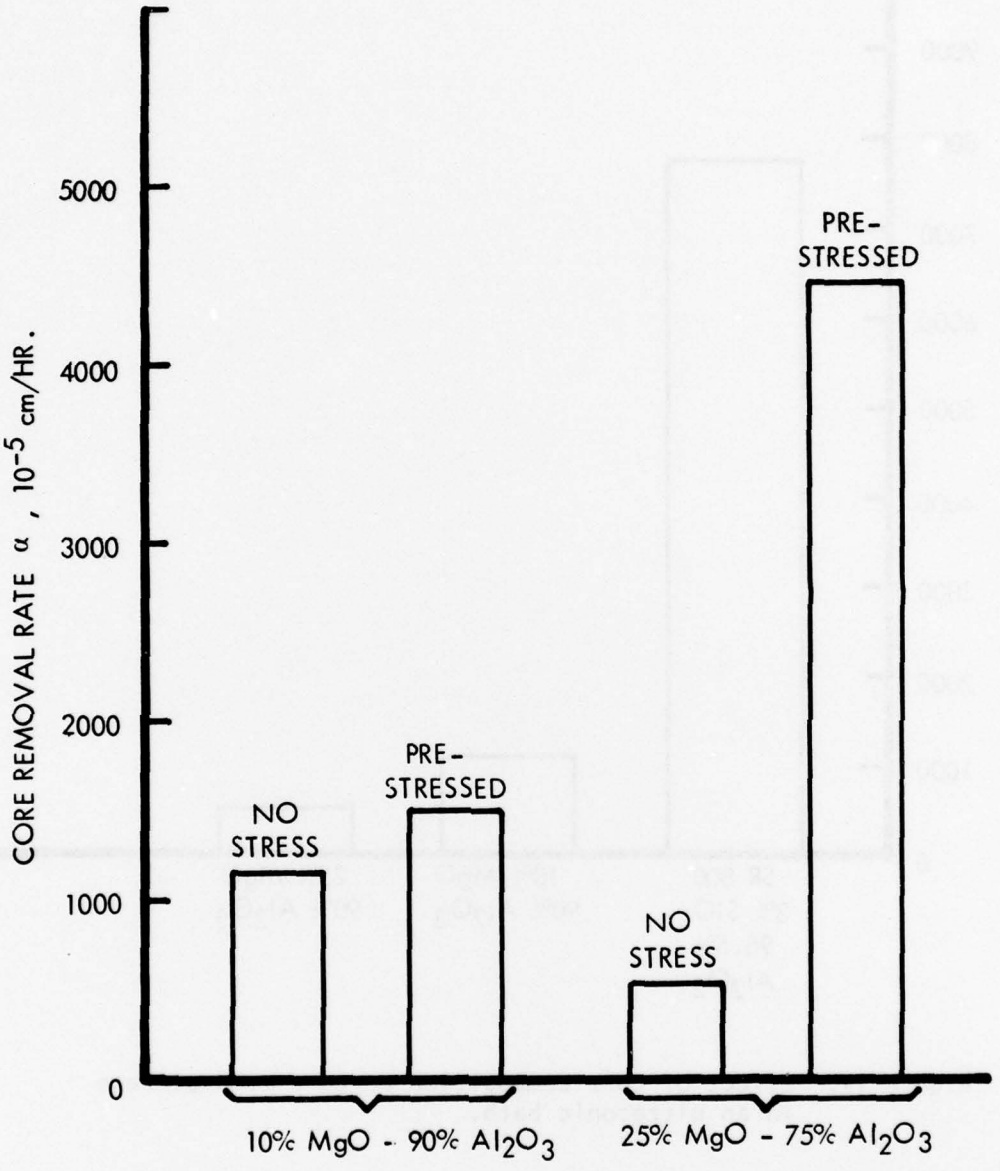


Figure 11. Effect of pre-stressing on core removal rate in an ultrasonic bath.

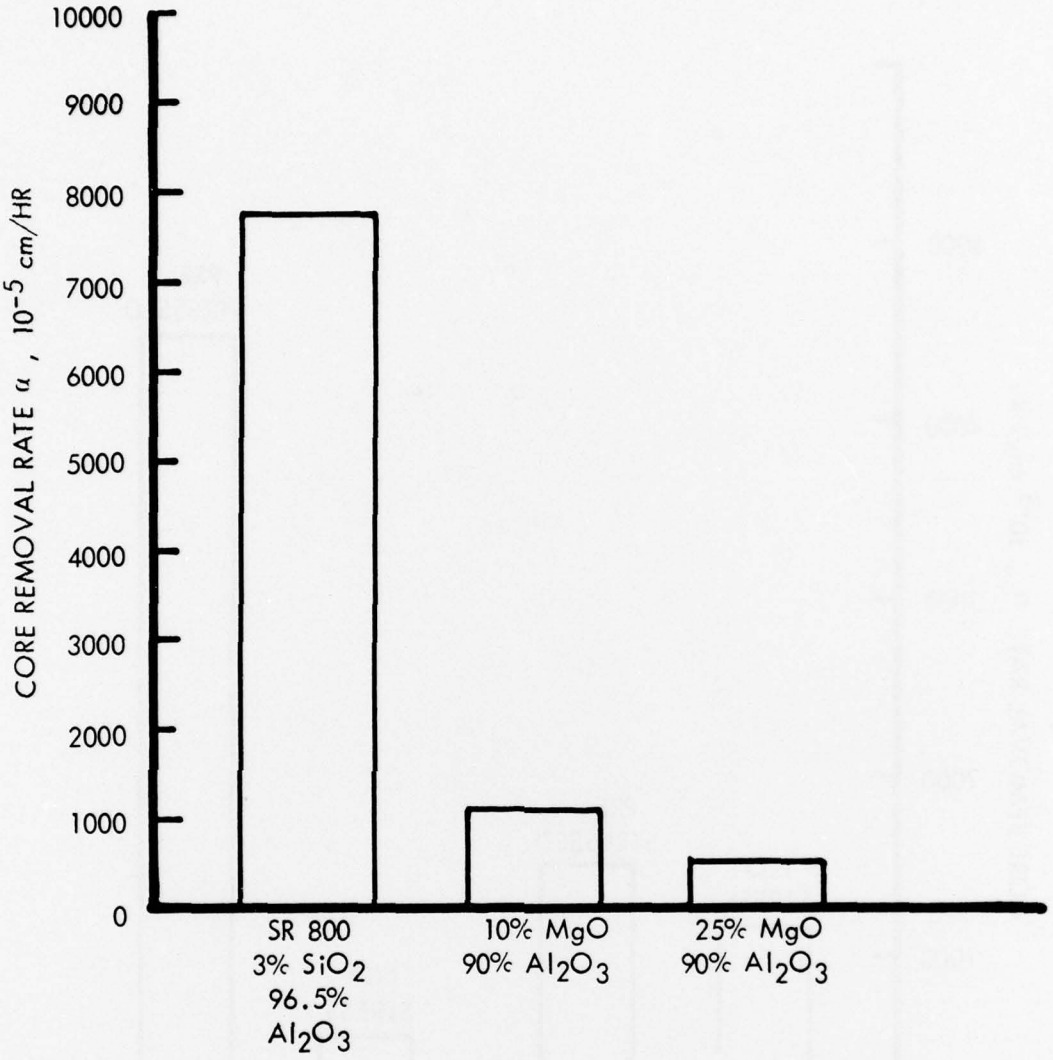


Figure 12. Effect of core composition on core removal rate in an ultrasonic bath.

2.3.5.3 Experimental Procedure - Ultrasonic Drill

One specimen of each of the three core materials was run with each of the drill bits. This provides a comparison both between core materials and between drill geometries. Specimens that had previously been run in the ultrasonic tank were also drilled to determine the effect of this prior exposure on drilling rate. Finally, specimens of the 10% MgO core material of three different geometries were run to determine the effect of specimen geometry.

The procedure was to clamp the casting in a fixture, and the generator and drill tip on a manually driven drill press. The bit was then pressed against the core material by moderate hand pressure on the handle. Initially, the casting was immersed in water to act as a couplant and to cool the part and drill bit. It was found, however, that a much higher penetration rate was achieved without couplant. The data listed in Table 5 was obtained with the casting partially immersed to provide cooling, but with no couplant. For the materials that were easy to drill, cooling was not necessary. It was used in all tests, however, because it was required for the difficult-to-drill materials. For specimens that were easy to dirll, the test was very short since it only took a minute or less for the drill to penetrate as far as it could reach. For the more difficult materials the tests were run for several minutes to assure that an easily measurable amount of material was removed.

2.3.5.4 Results - Ultrasonic Drill

The results of the experiments run using the ultrasonic drill are listed in Table 5. The effect of drill bit geometry was found to play an important role in determining core removal rate, as shown in Figure 13. The flat drill bit, while considerably better than the ultrasonic tank, did not compare in performance with the other two. Both the round and the rectangular drill bits provide excellent removal rates. The rectangular drill was significantly faster, presumably because its sharp corners concentrated energy to provide a quick initial entry point. However, because the round drill had a gradual taper while the rectangular drill increased rapidly in size, the round drill should be able to remove more total material in many applications. In actual practice, therefore, the choice of drill geometry should be determined by part geometry with a slight sacrifice in drilling rate made, if necessary, to gain maximum material removal. Since the ultrasonic drill is so much faster than the tank, maximum material removal with the drill will provide the shortest overall core removal time.

Drill tips were damaged drilling the 10% MgO-90% Al_2O_3 material, as shown in Figure 14. Little additional wear was noted when the SR 800 or 25% MgO-75% Al_2O_3 material was drilled. This experience underlines the importance of choosing the proper core material so as to obtain the most favorable process economics.

Table 5. Core Removal Tests on Castings Using Ultrasonic Drill

Sample No.	Material %MgO-%Al_2O_3	Cross-Sectional Geometry	Drill Bit	Run Time, T, hrs	Wt Loss, W, mg	Removal Rate, α, 10^{-5} cm/hr	Time to Remove 5g Core, hrs
8	0.3-96.5	4.8x12.7 mm	Flat	0.08	28.0	34,600	15
9	10-90	6.4 mm square	Flat	0.08	12.0	12,900	35
10	25-75	"	Flat	0.08	18.0	22800	23
11	0.3-96.5	4.8x12.7 mm	Round	0.01	401.0	23,800,000	0.1
12	10-90	6.4 mm square	"	0.09	40.0	114,000	20
13	25-75	"	"	0.16	721.0	688,000	4
2	10-90 (1)	6.4 mm square	"	0.09	1568.0	7,930,000	0.3
15	10-90	6.4 mm square	Rectangular	0.09	423.7	850,000	1.1
16	10-90	11 mm square	"	0.10	56.2	101,000	8.9
17	25-75	6.4 mm square	"	0.07	1092.3	3,530,000	0.3
18	0.3-96.5	4.8x12.7 mm	"	0.006	1723.0	60,600,000	0.02
2	10-90 (1)	6.4 mm square	"	0.05	955.7	3,450,000	0.3
4	25-75 (2)	"	"	0.13	1259.6	2,090,000	0.5
19	10-90 (3)	3.2x32 mm	"	0.042	13425	57,700,000	0.02
20	10-90 (3)	"	"	"	16690	71,700,000	0.01
21	10-90 (4)	"	"	"	1760	7,560,000	0.12
22	10-90 (4)	"	"	"	3270	14,100,000	0.06

(1) Specimen run in NaOH (93°C) in ultrasonic tank for 112.5 hrs. prior to drilling.
(2) Specimen run in NaOH (93°C) in ultrasonic tank for 10 hrs. prior to drilling.
(3) Both casting and core badly cracked. Drill removed core in large pieces.
(4) Core cracked on one end and easily removed by drill in this area only.

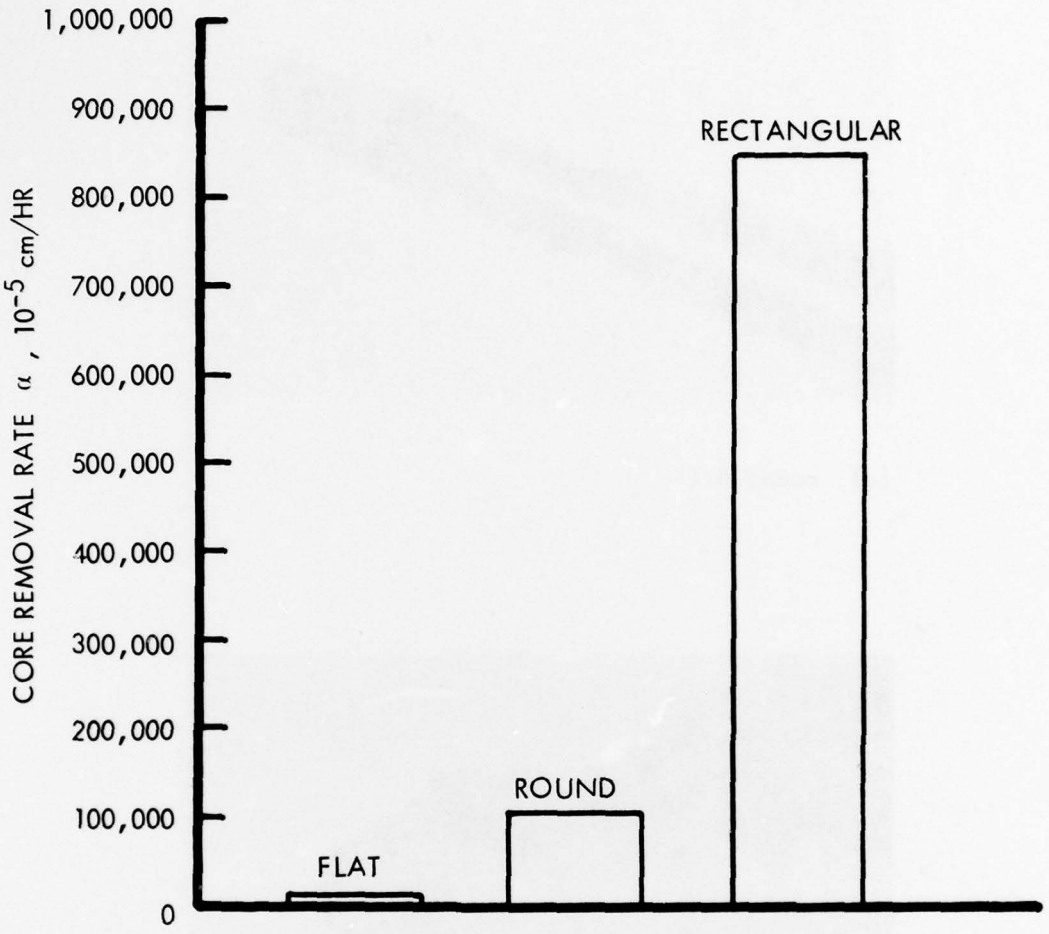
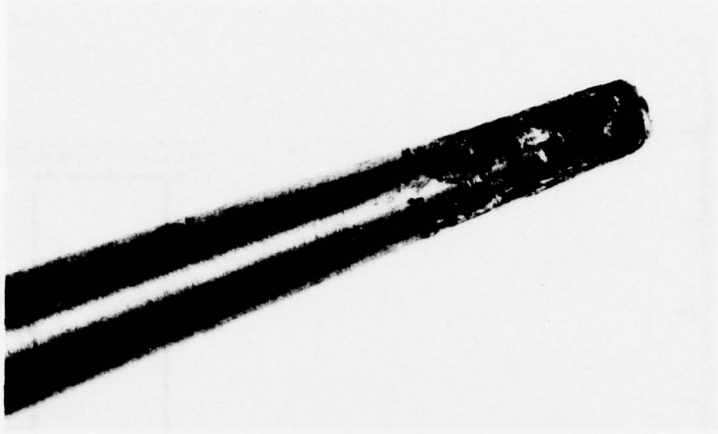
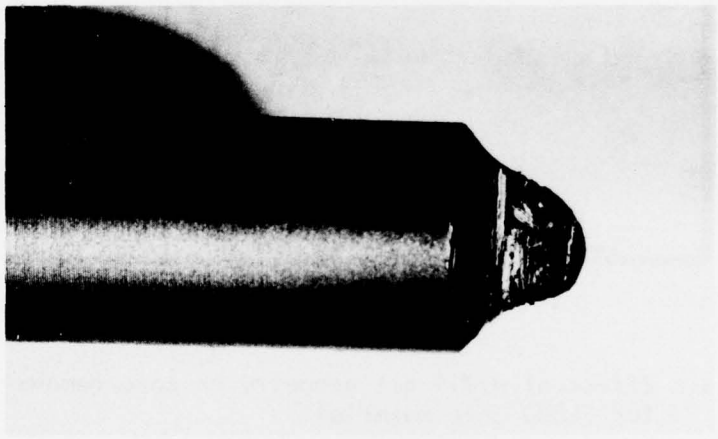


Figure 13. Effect of drill bit geometry on core removal rate for SR800 core material.



(a) round bit



(b) rectangular bit

Figure 14. Close-up of drill bits showing damage to bits resulting from use on 90% Al_2O_3 - 10% MgO spinel material.

Of the materials investigated, the SR 800 core body appears to satisfy the economic requirements. As shown in Figure 15, it is by far the easiest to remove. If the entire core were accessible to the drill, it could be removed in a few minutes. The 25% MgO core material is an order of magnitude more difficult to drill than the SR 800 and the 10% MgO core material is another order of magnitude more difficult to drill. The exception is the case of the 10% MgO core that was run for 112.5 hours in the ultrasonic tank in NaOH prior to drilling. This material was comparable to the 25% MgO core material. Again, this suggests that one possible strategy for hard-to-remove core materials might be to treat the castings in an ultrasonic bath before applying other core removal methods.

Core geometry also plays a role in core removal efficiency, as shown in Figure 16, which is a comparison of the results for the three different geometries of 10% MgO core material tested with the rectangular bit. The 10.9mm square core was an order of magnitude more difficult to drill than the 6.4mm square specimen, which in turn, was at least an order of magnitude more difficult than the 3.2 x 32mm rectangular cores. The apparent reason for this difference was the degree of cracking present prior to drilling. The 10.9mm square core was quite sound even at the ends where it was cut from the cluster. The 6.4mm square core showed some cracking. Two of the 3.2 x 32mm rectangular cores, 21 and 22, showed considerable cracking on one end and during drilling this was the area where most of the material removal occurred. The other two, specimens 19 and 20, were extensively cracked throughout and the drill was able to break loose large pieces, resulting in a very high removal rate. These results are similar in nature to the results in the ultrasonic tank on specimens that had been compressed. The cracking introduced into the core enhanced the rate of ultrasonic removal.

2.3.6 Metallurgical Effect of Ultrasonic Core Removal

Castings were sectioned after core removal and examined metallographically. No evidence of structural damage or alteration was detected. Casting surfaces were clean and intact and there was no evidence of chemical or mechanical attack.

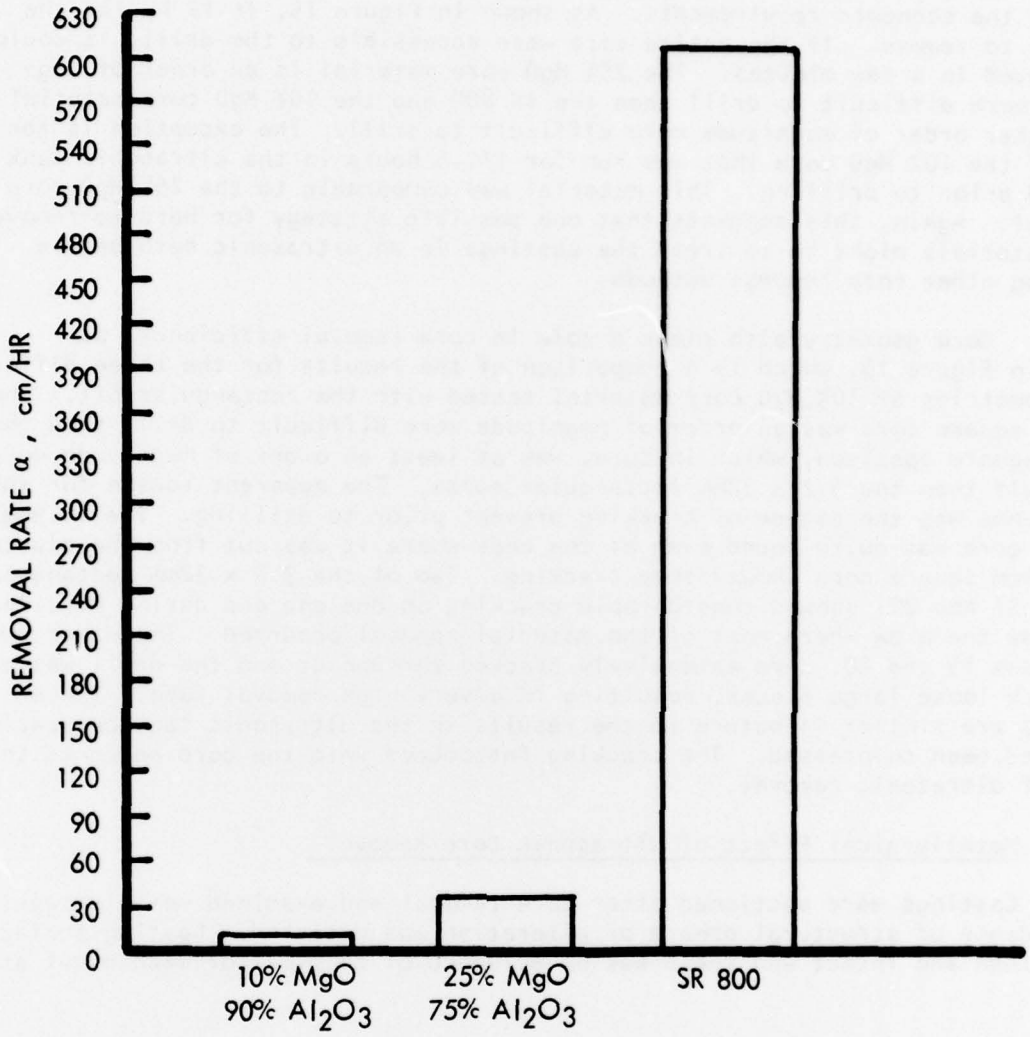


Figure 15. Effect of core composition on core removal rate using an ultrasonic drill.

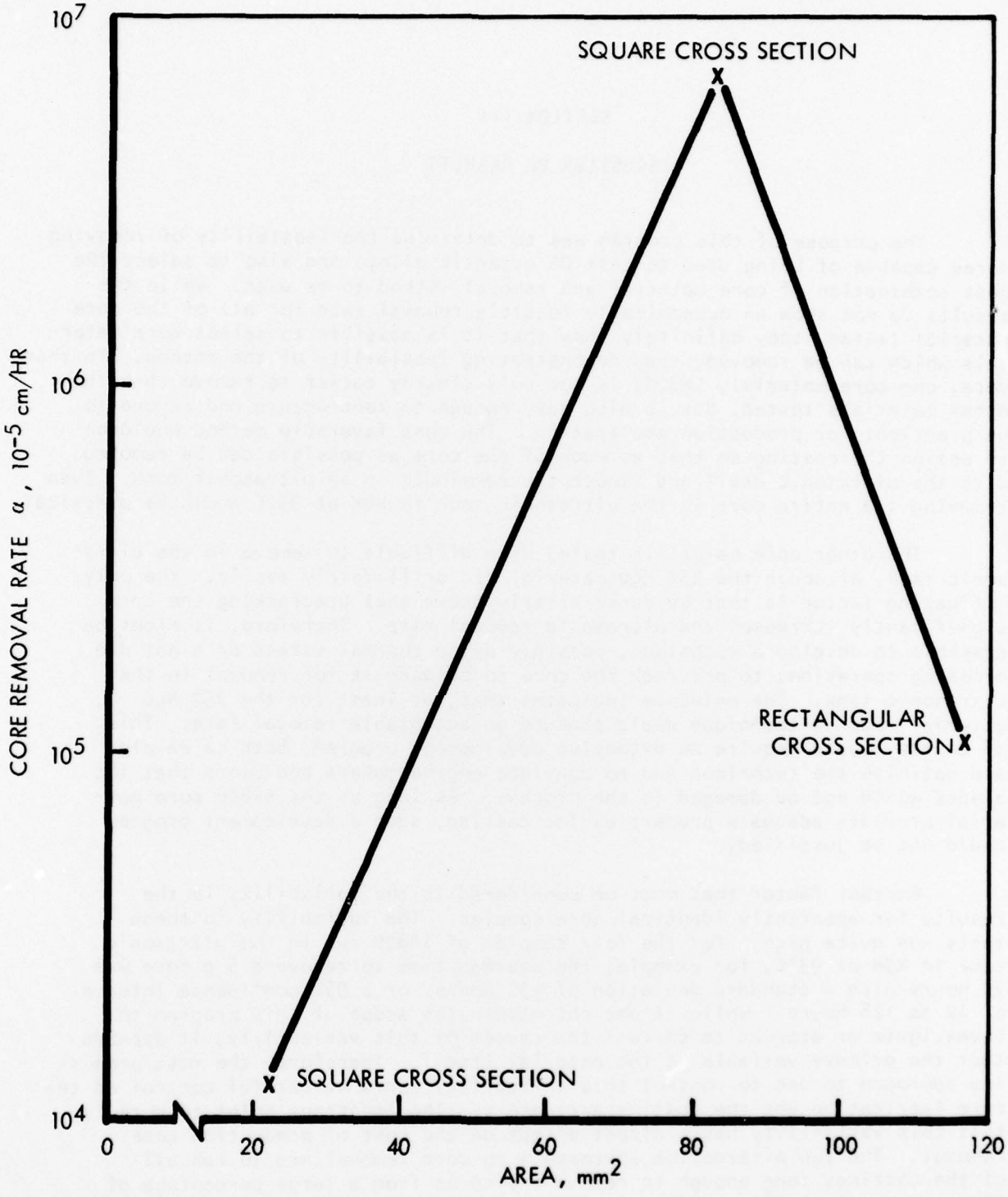


Figure 16. Effect of core geometry on core removal rate.

SECTION III

DISCUSSION OF RESULTS

The purpose of this program was to determine the feasibility of removing cores capable of being used to cast DS eutectic alloys and also to select the best combination of core material and removal method to be used. While the results do not show an economically feasible removal rate for all of the core material tested, they definitely show that it is possible to select core materials which can be removed, thus demonstrating feasibility of the method. Furthermore, one core material, SR800, is not only clearly easier to remove than the other materials tested, but is also easy enough to manufacture and remove to be practical for production application. The most favorable method would be to design the casting so that as much of the core as possible can be removed with the ultrasonic drill and remove the remainder in an ultrasonic tank. Even removing the entire core in the ultrasonic tank in KOH at 93°C would be practical.

The other core materials tested were difficult to remove in the ultrasonic tank, although the 25% MgO material did drill fairly easily. The only mitigating factor is that evidence clearly shows that precracking the core significantly increases the ultrasonic removal rate. Therefore, it might be possible to develop a technique, possibly using thermal stress or a hot die pressing operation, to precrack the core to prepare it for removal in the ultrasonic tank. The evidence indicates that, at least for the 25% MgO material, such a technique would produce an acceptable removal rate. This, of course, would require an extensive development program, both to develop and optimize the technique and to convince engine makers and users that the blades would not be damaged in the process. As long as the SR800 core material provides adequate properties for casting, such a development program could not be justified.

Another factor that must be considered is the variability in the results for apparently identical core samples. The variability in these tests was quite high. For the four samples of SR800 run in the ultrasonic tank in KOH at 93°C, for example, the average time to remove a 5 g core was 70 hours with a standard deviation of $\pm$32 hours, or a 95% confidence interval of 12 to 128 hours. While it was not within the scope of this program to investigate or attempt to correct the causes of this variability, it appears that the primary variable is the material itself. Therefore, the most promising approach to use to control this variability would be careful control of the core fabrication and the casting parameters. The important point to note is that this variability has a direct effect on the cost of production core removal. The two alternative approaches to core removal are to run all of the castings long enough to remove the cores from a large percentage of them, or to check the castings periodically and remove those that are done. The former method is preferable if the variability is small. With a large variability, however, this means running the majority of the parts in the

ultrasonic cleaner long after the cores have been removed. In such a case it might be preferable to check the castings periodically. In an actual production situation the preferred method would have to be determined by a careful evaluation of the economic factors involved in the overall production process.

The development of LDGA core material(10) came too late for this material to be included in this program. Its porous structure, however, suggests that the application of ultrasonic energy to the core body would enhance core removal and it is recommended that such experiments be carried out so as to obtain the most rapid core removal possible for this material.

It is important to recognize that the most difficult material to remove was 95% Al_2O_3 while the easiest was 96.5% Al_2O_3 with only the remaining few percent being different. This points out that it is the phase structure of the core material that determines removability and not simply its composition. It is concluded, therefore, that core materials should be formulated with ultrasonic removability in mind and that any new core materials considered should be examined for ultrasonic removability.

Of the materials studied, 3 + mol % SiO_2 - 96.5 + mol % Al_2O_3 .3 mol % MgO - 0.1 mol % Fe (SR800) was found to be the best material. It showed good casting properties and was found to be easily removable by both the ultrasonic drill and the ultrasonic tank containing KOH at 93°C. If the entire core were accessible, the ultrasonic drill could remove a 5 g core in a few minutes. The average removal rate of a 5 g core in the ultrasonic tank is 70 $\pm$ 32 hours. Therefore, while use of the ultrasonic drill in accessible areas would increase the removal rate, this material would be practical to remove in the ultrasonic tank alone. As this material is injection molded, it can be formed into the complex shapes required for aircooled turbine blades with relative ease.

SECTION IV

CONCLUSIONS

The following conclusions may be drawn from the results of this program:

1. The application of ultrasonic energy to cored castings comprises a rapid core removal method.

2. Focused ultrasonic energy, i.e., the use of an ultrasonic drill, is more efficient than the use of ultrasonic bath in removing cores.

3. A promising core material for use in the manufacture of NiTaC-13 castings is made up of 3 + mol % SiO_2 - 96.5 + mol % Al_2O_3 - 0.3 mol % MgO - 0.1 mol % Fe (designated SR800[2] by its manufacturer,[3] Sherwood Refractories, Inc., Cleveland, Ohio).

4. Removability of MgO-Al_2O_3 (spinel) core bodies increases as the percentage of MgO increases[3] and is enhanced by precracking the core and immersion in a bath made up of a saturated solution of KOH.

5. Core removability is influenced by core geometry and the degree to which the core is cracked prior to exposure to ultrasonic energy.

6. A suitable core removal strategy for complex shapes consists of drilling the major areas of the core from the casting and immersing the casting containing residual core material in an ultrasonic bath at a moderately elevated temperature in a saturated caustic solution.

APPENDIX

The following are the critical parameters for effective removal of 3 + mol % SiO_2 - 96.5 mol % Al_2O_3 - 0.3 mol % MgO - 0.1 mol % Fe core material:

1. Ultrasonic Tank

   Energy Density - 5.5 w/cm^2

   Solution in Tank - saturated solution of KOH in water

   Temperature - 93°C

   Time - 70 $\pm$ 32 hours

2. Ultrasonic Drill

   Energy Density - 3500 w/cm^2

   Couplant - none

   Feed Rate - 10 cm/minute

   Bit Geometry - rectangular

Other parameters, such as voltage, power ratine of the generator, capacity, drill bit dimensions are not critical and should be selected to conform to the above requirements and to requirements of the particular type and number of parts being processed.

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